FACULTY OF MECHANICAL ENGINEERING
UNIVERSITY OF WEST BOHEMIA

DEPARTMENT OF
POWER SYSTEM ENGINEERING

KKE/ESV – Solar and Wind Energy

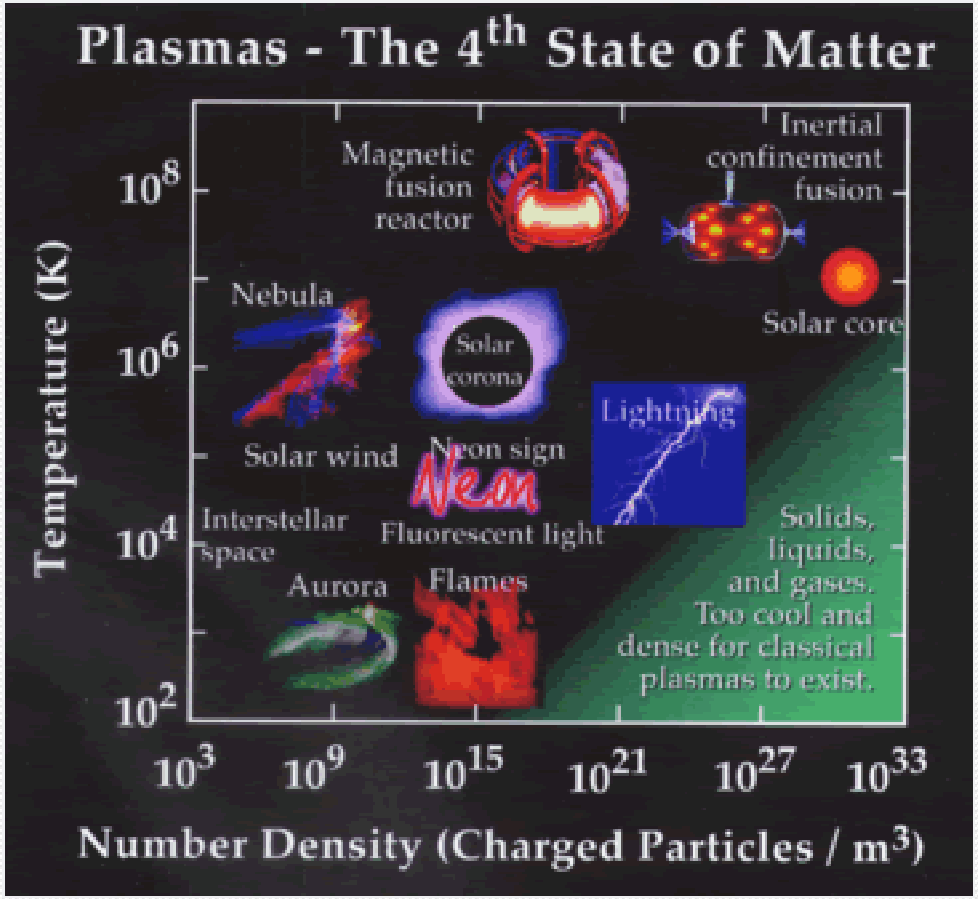
2019/2020
2nd lecture

Content

- Physics of the Sun and solar radiation
- Solar constant and insolation
- Solar thermal systems (collector systems)
- Photovoltaics and PV panels
- Concentrated solar power (CSP)

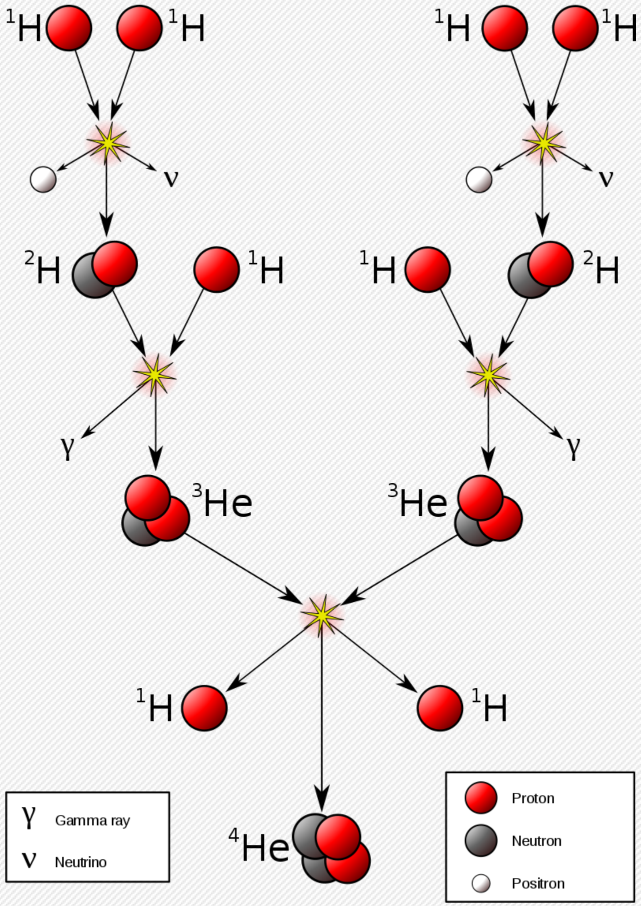
Origin of solar radiation

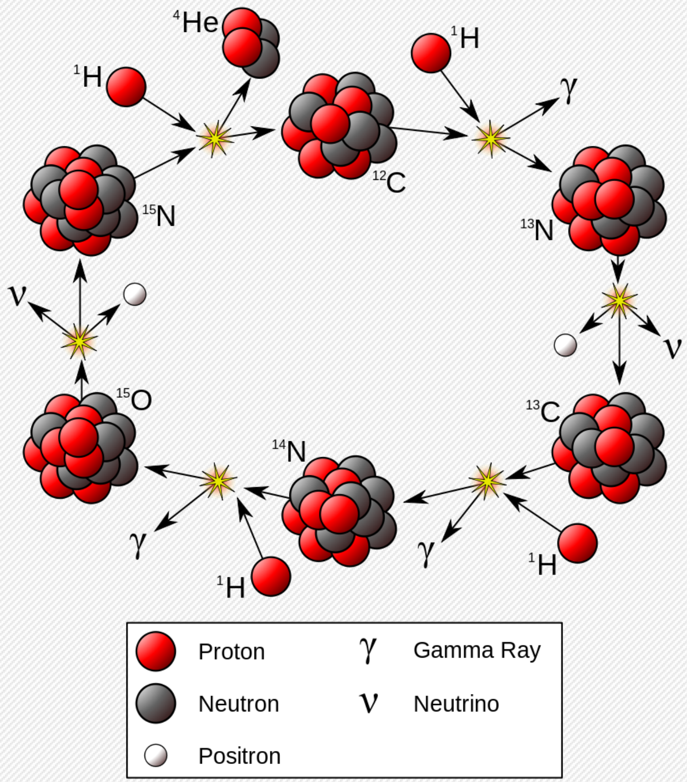
- Solar energy is generated by nuclear reactions in the central regions of the Sun. It is a nuclear fusion reaction that is often described as thermonuclear fusion.
- What are the conditions inside the Sun's core?
    - A temperature of about 15 million Kelvin
    - High pressures around 2.48 PPa (petapascals, 10^{15})
    - Density 100 times higher than water density, i.e. that 1 dm^3 of this environment weighs about 100 kg.
    - The mass is here in the plasma state, that is, when the electron shell is torn away from the core of the element.



Proton–proton chain reaction

The proton–proton chain reaction is one of two known sets of nuclear fusion reactions by which stars convert hydrogen to helium. It dominates in stars with masses less than or equal to that of the Sun's, whereas the CNO (carbon-nitrogen–oxygen) cycle, the other known reaction, is suggested by theoretical models to dominate in stars with masses greater than about 1.3 times that of the Sun's. Proton-proton chain reaction involves 3 steps.





Proton-proton chain reaction

1. $^{1}H + {}^{1}H \rightarrow {}^{2}D + e^{+} + \upsilon$ $+ 0.42$ MeV

In this reaction, the protons of the hydrogen react to form a heavier hydrogen isotope, deuterium (D). There is also a positron and a neutrino because two reactions are actually taking place.

$^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{2}He$

$^{2}_{2}He \rightarrow {}^{2}_{1}H^{-} + e^{+} + \nu_e$

BETA-PLUS DECAY
WEAK NUCLEAR FORCE
BILION YEARS

positron emission of diproton to deuterium is extremely rare

Since the positron and electron (from the environment) behave anti-particle toward each other, their annihilation occurs very quickly, during which these two particles disappear. Their mass and kinetic energy is converted into a gamma photon beam and radiated into space.

$e^{-} + e^{+} \rightarrow 2\gamma + 1.022$ MeV

In addition, the first step produces a neutrino that usually does not participate in other nuclear reactions and can be detected on Earth.

Proton–proton chain reaction

2. $^{2}_{1}D + ^{1}_{1}H \rightarrow ^{3}_{2}He + \gamma + 5.49\ MeV$

STRONG NUCLEAR FORCE
FEW SECONDS
deuterium exists for about 4 seconds

In the second step, the deuterium nuclei reacts with the hydrogen proton to form a light helium isotope called helium-3. At the same time, a bundle of gamma photons is created.

Once a helium-3 light isotope is formed, it is converted to a stable helium nucleus (helium-4). The conversion to the stable helium nucleus can take place in 4 ways with different probabilities. Thus, the third step can be carried out differently. Each helium-3 nucleus produced in these reactions exists for only about 400 years before it is converted into helium-4.

Proton–proton chain reaction – 3rd step

A total of 4 reactions are formed with the most frequent (83.30%) reaction of two helium-3 nuclei:

$$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + 2\,^{1}_{1}H + 12.86\ MeV$$

The second most common (16.68 %) leads to helium-4 through the formation of isotopes of beryllium and lithium:

$$^{3}_{2}He + ^{4}_{2}He \rightarrow ^{7}_{4}Be + \gamma$$
$$^{7}_{4}Be + e^{-} \rightarrow ^{7}_{3}Li^{-} + \nu_e + 0.861\ MeV\ /\ 0.383\ MeV$$
$$^{7}_{3}Li + ^{1}_{1}H \rightarrow 2\,^{4}_{2}He$$

The third most common (0.02%) leads to helium-4 through the formation of beryllium and boron isotopes:

$$^{3}_{2}He + ^{4}_{2}He \rightarrow ^{7}_{4}Be + \gamma$$
$$^{7}_{4}Be + ^{1}_{1}H \rightarrow ^{8}_{5}B + \gamma$$
$$^{8}_{5}B \rightarrow ^{8}_{4}Be + e^{+} + \nu_e$$
$$^{8}_{4}Be \rightarrow 2\,^{4}_{2}He$$

The fourth and rarest is theoretically assumed, but has never been observed (helium-3 captures a proton directly to give helium-4):

$$^{3}_{2}He + ^{1}_{1}H \rightarrow ^{4}_{2}He + e^{+} + \nu_e + 18.8\ MeV$$

Energy released

Mass Balance:

- We do not have to consider photons in the mass balance because they have zero mass energy and neutrinos, which can also be neglected for this balance. For a long time, the neutrino was considered to be an intangible particle, but recent research shows a non-zero mass energy, but immeasurable by current possibilities.
- The mass of proton expressed by atomic mass unit (1u = 1.6605402 · 10^{-27} kg) is 1.0075 u.
- Mass balance, the difference in mass of particles before and after reaction:

Before:	Mass of 4 hydrogen atoms	4 x 1.0075 u = 4.0300 u
After:	Mass of helium	4.0013 u
<u>Difference:</u>		0.0287 u

- The mass of 0.0287 u was converted into radiation, in the energy of photons.

$$E = m \cdot c^2 = 0{,}0287 \cdot 1{,}6605402 \cdot 10^{-27} \cdot 299\,792\,458^2 = 4{,}28 \,.\, 10^{-12} \text{ J} \quad \approx 26.73 \text{ MeV}$$

Energy released

- The mass of one hydrogen nucleus (proton) is $1.67 \cdot 10^{-27}$ kg = $1.67 \cdot 10^{-24}$ g.
- Therefore, 1 gram of hydrogen contains $1 / 1.67 \cdot 10^{-24} = 5.99 \cdot 10^{23}$ nuclei.
- The conversion of 1 gram of hydrogen into helium releases:

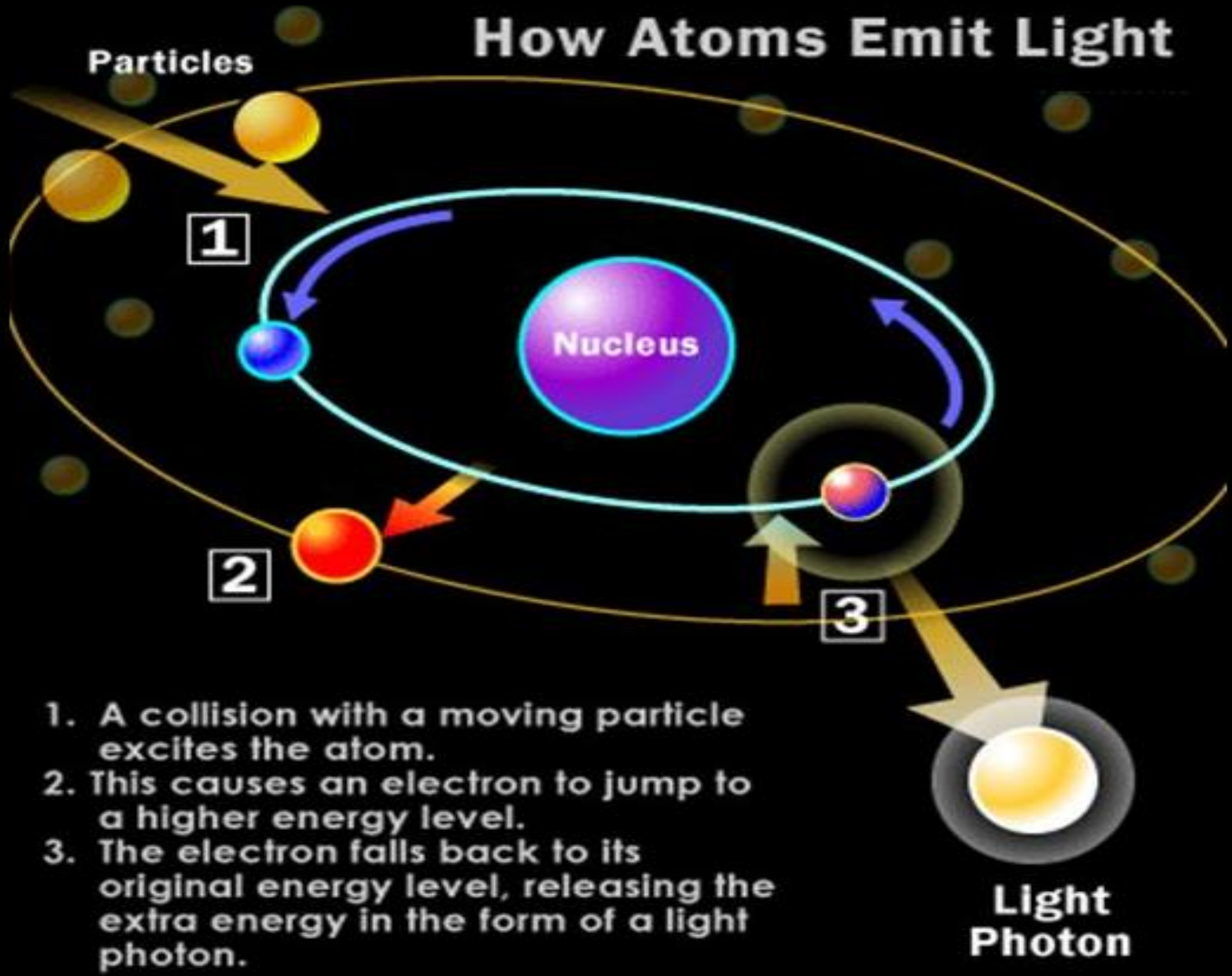
  $4.28 \cdot 10^{-12} \cdot 5.99 \cdot 10^{23} / 4 = 641$ GJ

- It's really a lot of energy, considering that within one second, 560 million tons of hydrogen are converted into helium. This, however, reduces the mass of the Sun by 4 million tons every second.
- It seems a lot, but due to the mass of the Sun, it is a lot of nothing. It would take 45 million years for the mass of the Sun to drop by one Earth's mass by radiation, the Earth's weight being only 1/300,000 of the Sun's mass.

Photons released

- The photons released by the thermonuclear reaction are high energy photons and have even higher energy than the generally more well known high energy X-rays. The process of photon flight from the Sun's core to its surface takes about one to two million years.
- During this time there are changes of direction, many collisions with electrons and ions contained in the outer parts of the Sun (photon + ion => electron punching, electron + ion => a photon with changed energy is produced).
- Therefore, most high-energy photons turn into lower-energy photons, so there is so-called "photon crumbling". The whole process of penetrating photons from the interior of the Sun to the surface is called photon leakage. During leakage, one photon formed in the interior of the Sun can appear on its surface (in the so-called photosphere) as 2.5 thousand light photons.

Photon Model



Light is made of particles or bundles of energy that travel in a beam or stream.

Photon energy

- The photon energy can be expressed as:

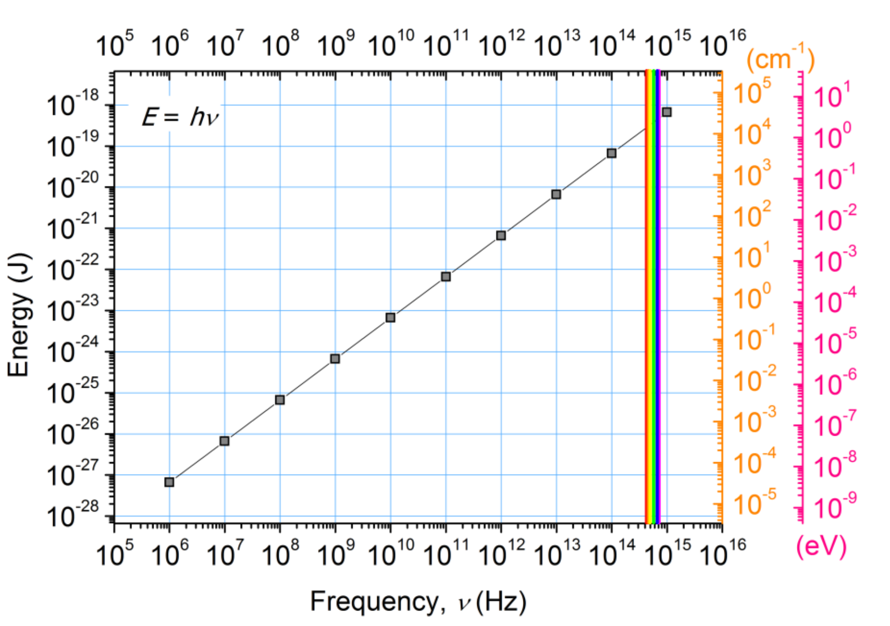
$$E = h \cdot f = h \cdot \frac{c}{\lambda}$$

h … Planck's constant ($h = 6.626196 \cdot 10^{-34}\ J \cdot s$)

f … photon (radiation) frequency [s^{-1}]

c … speed of light [m/s] (299,792,458 m/s)

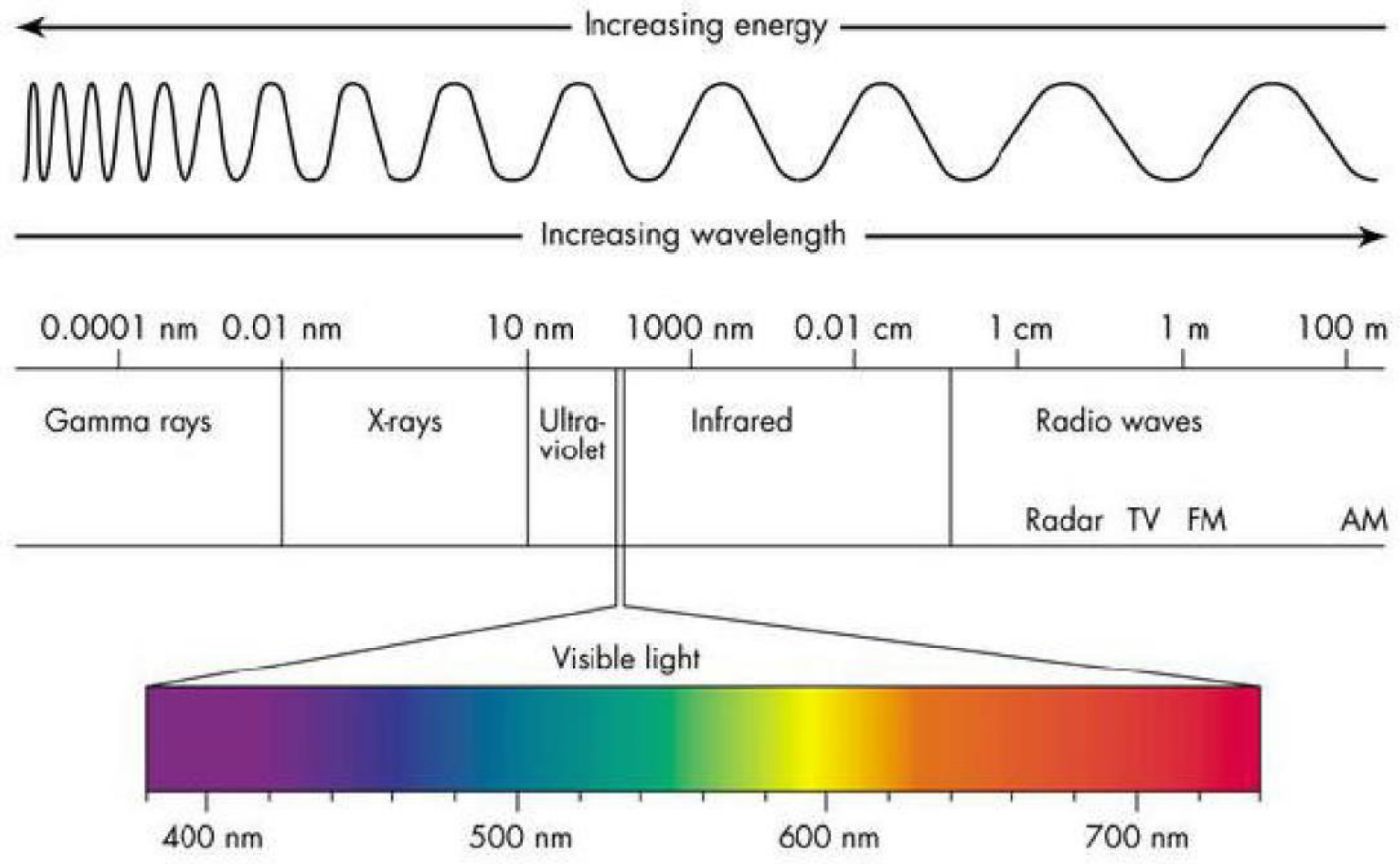
λ … radiation wavelength [m]

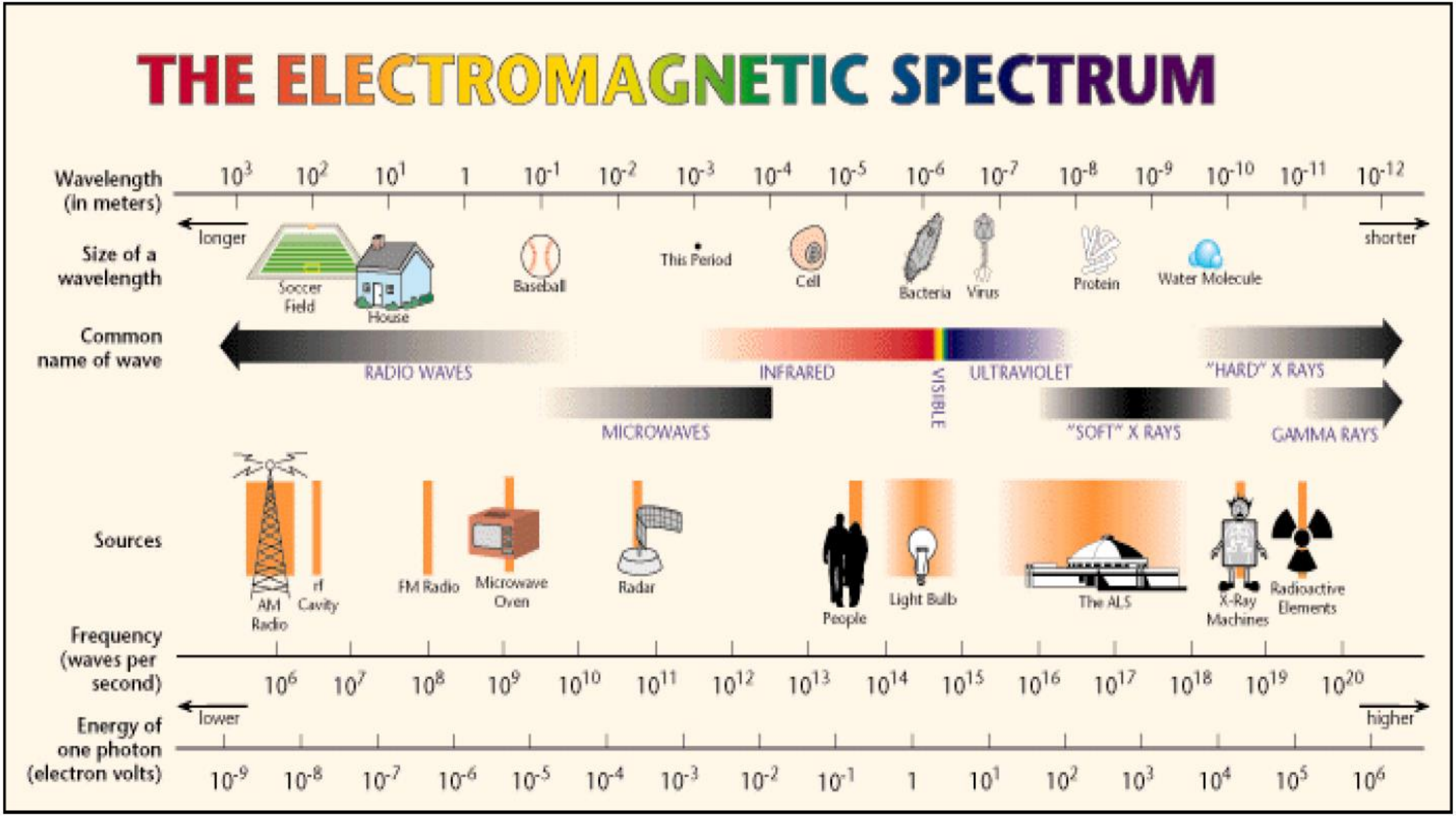


- This means that high-energy photons have a higher frequency than lower-energy photons, and therefore, the radiation has a lower wavelength.

Electromagnetic radiation

Photons are electromagnetic radiation and according to wavelengths (frequencies) these radiations are specifically named, gamma rays, X-rays, ultraviolet, visible radiation, infrared, radio waves. Visible radiation is characterized by a wavelength interval of about 400 (violet) to about 800 nm (red).

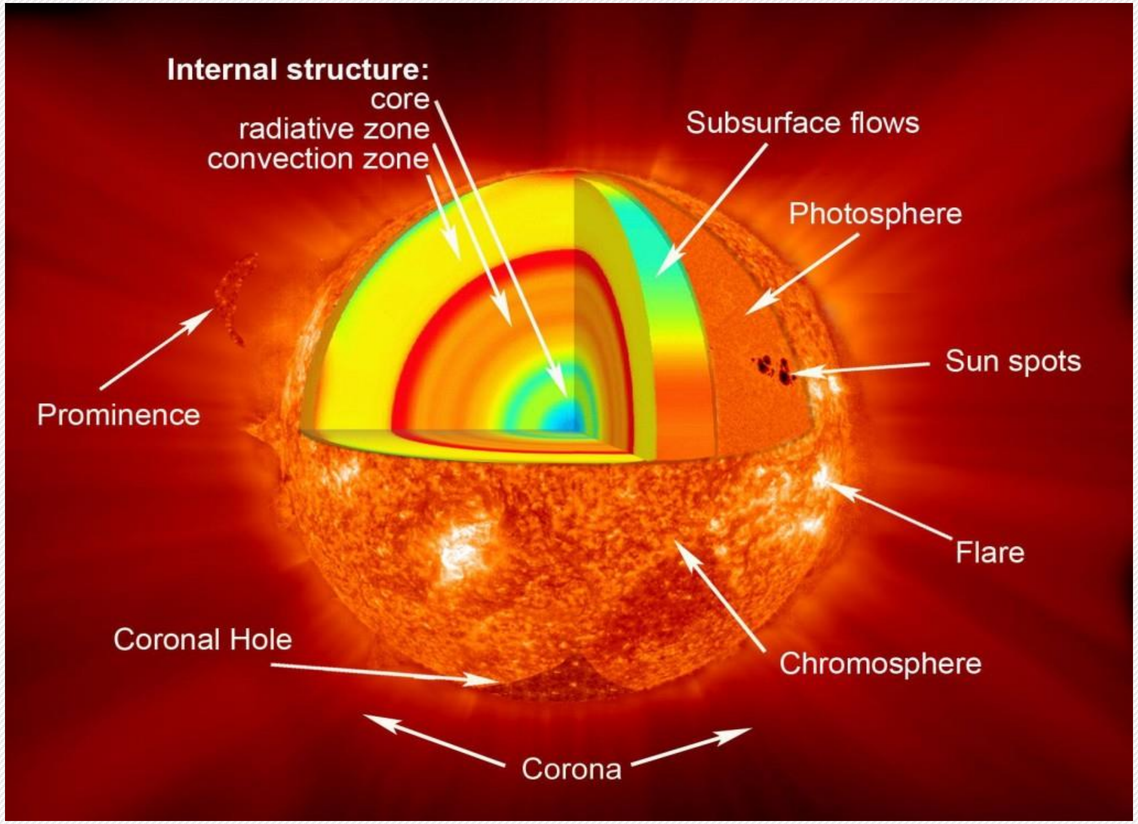




THE ELECTROMAGNETIC SPECTRUM
Wavelength (in meters)
10^3 10^2 10^1 1 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11 10^-12
longer
shorter
Size of a wavelength
Soccer Field
House
Baseball
This Period
Cell
Bacteria
Virus
Protein
Water Molecule
Common name of wave
RADIO WAVES
INFRARED
VISIBLE
ULTRAVIOLET
"HARD" X RAYS
MICROWAVES
"SOFT" X RAYS
GAMMA RAYS
Sources
AM Radio
rf Cavity
FM Radio
Microwave Oven
Radar
People
Light Bulb
The ALS
X-Ray Machines
Radioactive Elements
Frequency (waves per second)
10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
lower
higher
Energy of one photon (electron volts)
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 1 10^1 10^2 10^3 10^4 10^5 10^6

Sun – Structure of the Sun

- **Core** – slow conversion of hydrogen to helium.
- Layer in a radiant equilibrium (**radiative zone**) – causes photon retardation.
- **Convective zone** – streams of hot plasma.
- **Photosphere** – visible sun surface.
- **Chromosphere** – thin layer above the surface.
- **Corona** – "upper atmosphere" of the sun.



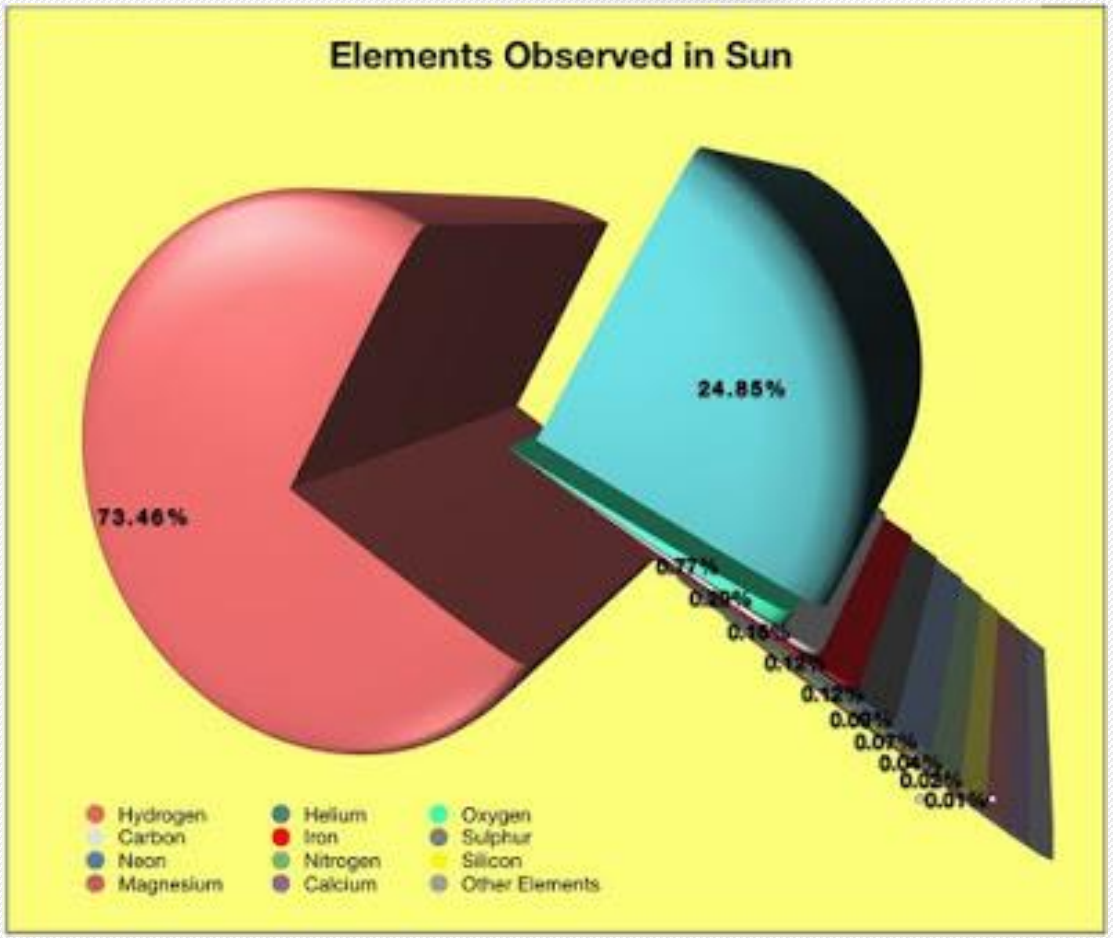
Sun – Physical characteristics

Power	4.10^{26} W (0,19 mW/kg)	Core Density	130 g/cm^3
Diameter	$1,39.10^{6}$ km (109x Earth)	Surface Density	0,001 g/cm^3
Surface	$6,09.10^{12}$ km^2 (11 900x Earth)	Surface Gravity	273,95 m/s^2 (27,9 G)
Volume	$1,41.10^{18}$ km^3 (1 300 000x Earth)	Core Temperature	13,6 MK
Weight	$1,99.10^{30}$ kg (332 950x Earth)	Corona Temperature	5 MK
Ø Density	1,41 g/cm^3 (Earth - 5,52 g/cm^3)	Surface Temperature	5 780 K

- The Sun is currently 4.6 billion years old and has a lifetime of 7 billion years.
- After the photon leaves the solar corona, it takes 500 seconds to reach Earth.

Composition of the Sun

- With the development of spectroscopic methods it was possible to determine quite precisely the composition of the Sun, which consists mainly of hydrogen (92.1%) and helium (7.8%). A small residue is oxygen, carbon, nitrogen, neon, iron, silicon, magnesium and sulfur. It follows that the mass of the Sun is practically made up of only hydrogen (75%) and helium (25%).



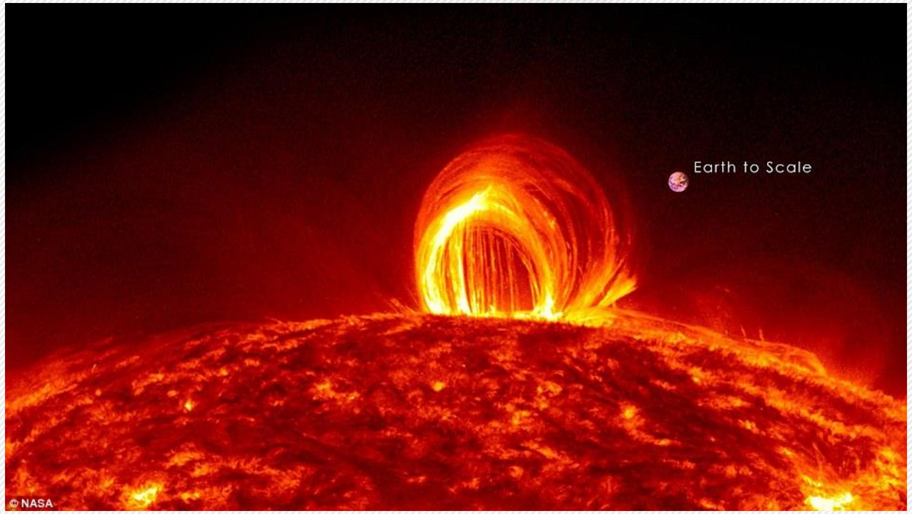
Exterior Sun effects

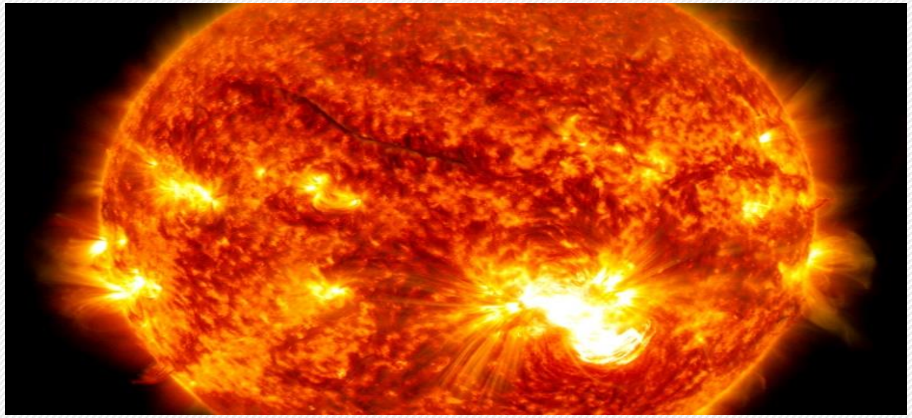
Solar prominence

- Solar mass jets
- Tens of thousands of kilometers above the surface
- Curvature according to local magnetic field

Solar flares

- Brightening in photosphere and chromosphere
- Significant release of matter and energy
- Tearing off a cloud with a frozen magnetic field - aurora, magnetic storms





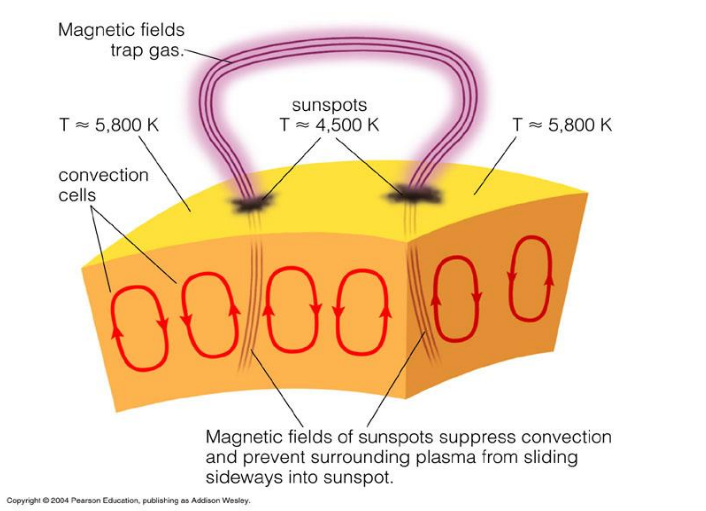
Exterior Sun effects

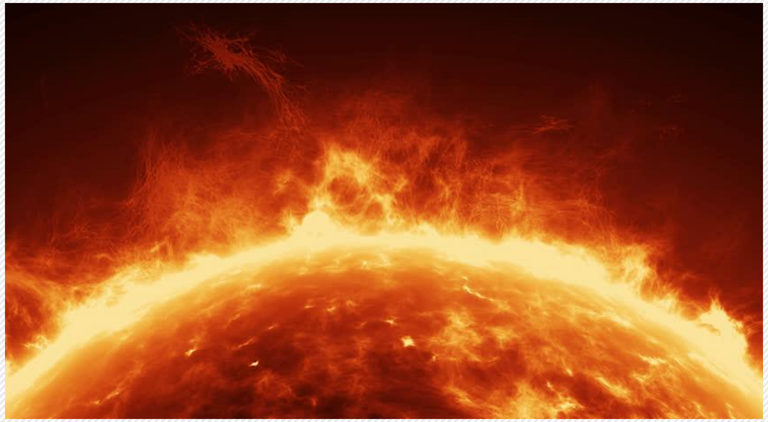
Sunspots

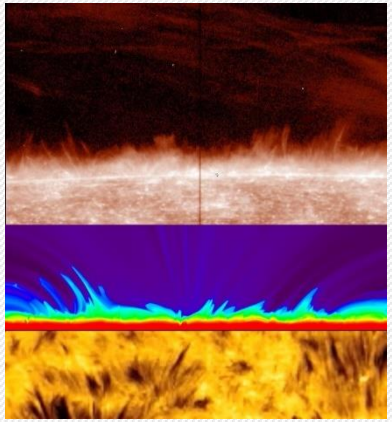
- Dark areas on the lower temperature surface
- They arise from the interaction of the magnetic field
- Size up to 50,000 km in diameter

Solar spicules

- Narrow jets of solar matter
- Thousands of kilometers above the surface
- Lifetime a few minutes







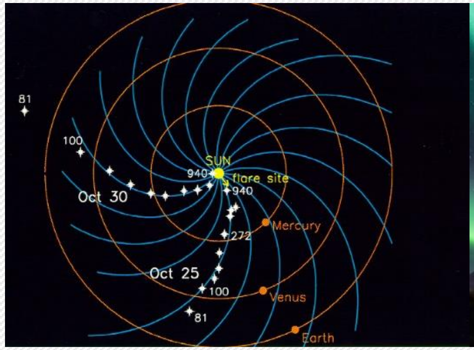
Exterior Sun effects

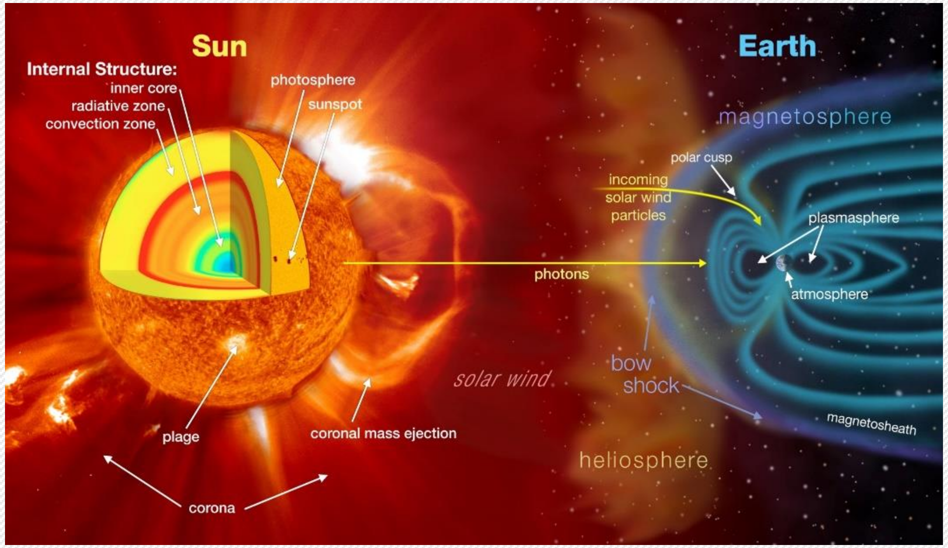
Magnetic field

- Influenced by the rotation of the sun
- Field lines in the shape of Archimedes spirals
- Zero field in equatorial region
- Planets pass through areas with different fields

Sun wind

- Charged particle current (ripped off by radiation pressure)
- Creates the outer atmosphere of the sun – corona
- Shapes the planet's magnetic field
- Aurora, magnetic storm





Links to investigate

- https://en.wikipedia.org/wiki/Proton%E2%80%93proton_chain_reaction
- https://www.youtube.com/results?search_query=structure+of+sun
- https://www.youtube.com/results?search_query=physics+of+sun
- https://www.youtube.com/results?search_query=proton+proton+cycle
- https://www.youtube.com/results?search_query=sun+properities
- https://www.youtube.com/results?search_query=electromagnetic+spectrum
- https://www.youtube.com/results?search_query=photons+physics
- or google it…

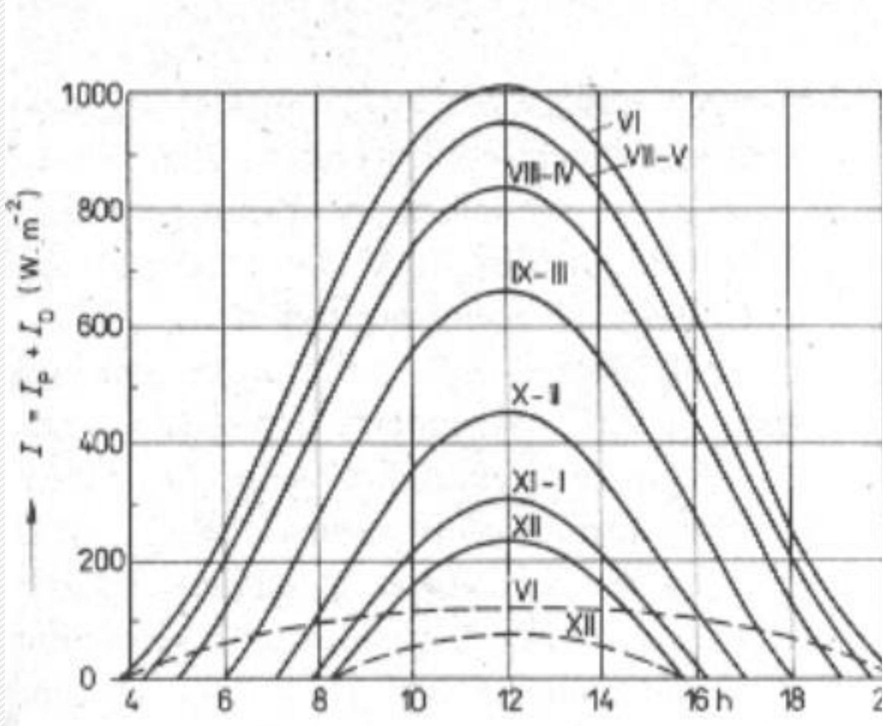
Radiation intensity

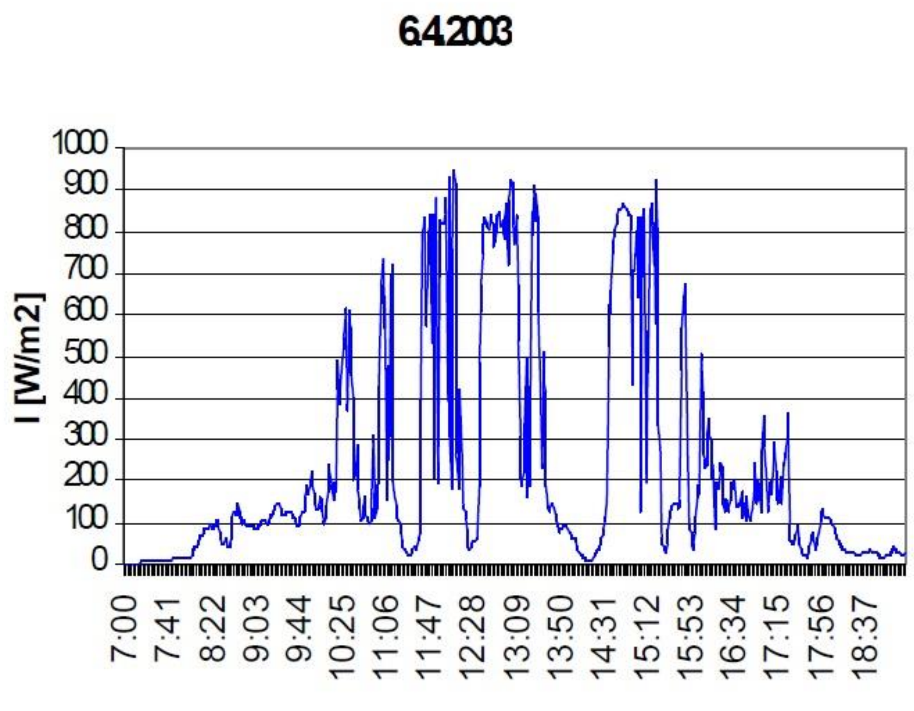
- Defines the power input of the device, changes during the day and year

$$I = I_P + I_D$$

Radiation is composed of direct usable (casts a shadow) and diffuse radiation (scattering and reflection in the atmosphere)

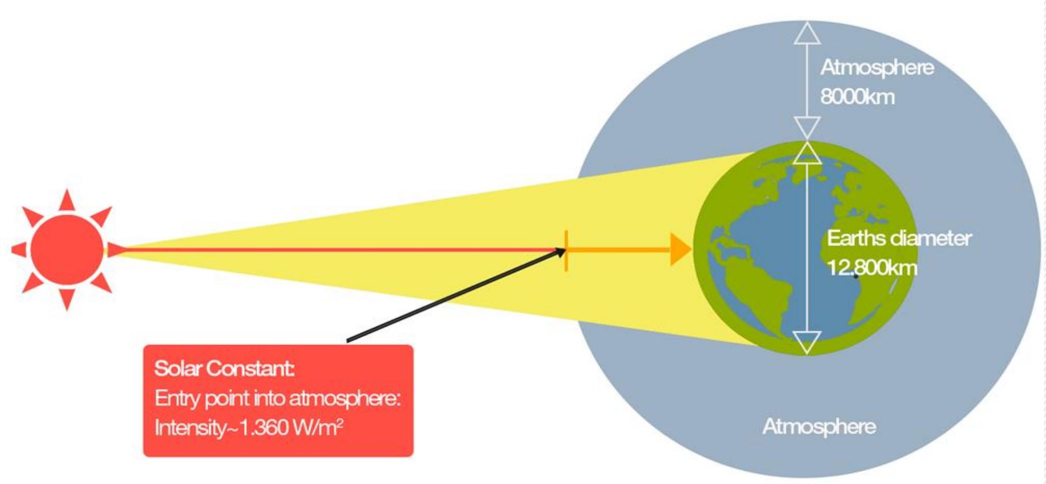
- Clear sky $I = I_P$
- Cloudiness $I = I_D$





Solar constant

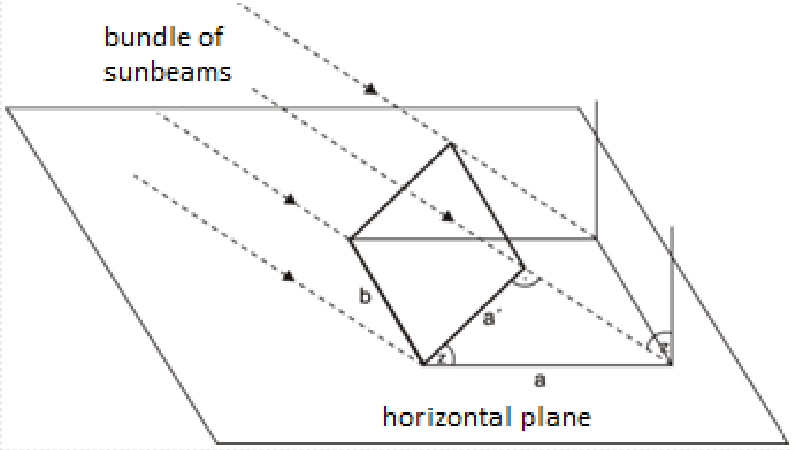
$$I_0 = 1360\ W/m^2$$

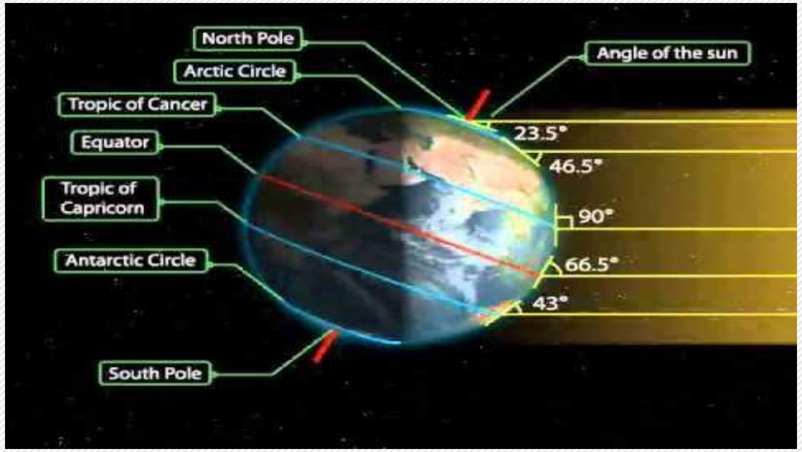


- Intensity of radiation incident perpendicular to the atmosphere boundary.. The constant includes the entire spectrum of sunlight, not just visible light.
- Part absorbed and reflected by the atmosphere - about 1000 W/m^2 on the surface.
- Defined by instant sun power and current position Earth – Sun and as the Earth's orbit is slightly eccentric, the actual energy flow on Earth fluctuates slightly over the year. Deviations from the solar constant value are approximately +/- 3 %.

Insolation

- Insolation (intensity of direct solar radiation incident on the horizontal surface of the earth's surface) is essential for energy use - radiation does not reach the surface perpendicularly due to the inclination of the Earth's axis, the zenith distance of the Sun changes => The insolation value varies considerably (unlike the solar constant) and decreases by up to 60% from the equator towards the poles (it is therefore significantly variable depending on the day and year and latitude)!
- The insolation on the horizontal surface a.b will be less than on the unit of the surface a´.b, which is perpendicular to the direction of the sun's rays. The greater the angle of incidence of the sun's rays (the higher the Sun is in the sky), the shorter the path the rays must travel and the more energy is absorbed per unit area.



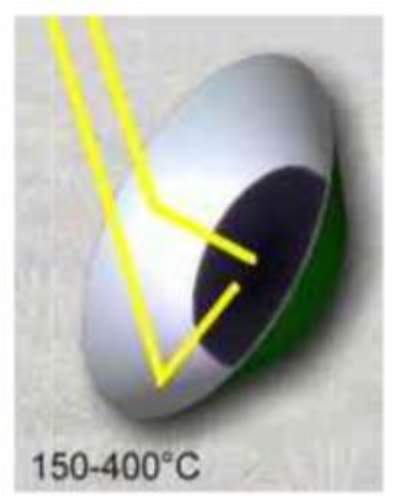


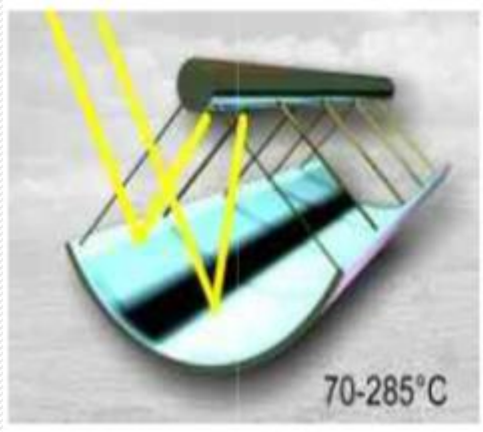
Links to investigate

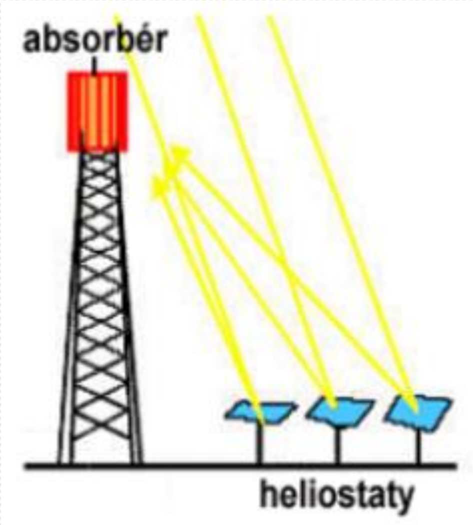
- https://www.youtube.com/results?search_query=solar+constant
- https://www.youtube.com/results?search_query=solar+radiation
- https://www.youtube.com/results?search_query=solar+insolation
- or google it…

Types of solar installations

- Photovoltaic panels - silicon or other semiconductors, organic compounds
- Collectors - planar or focusing (concentration using mirrors)

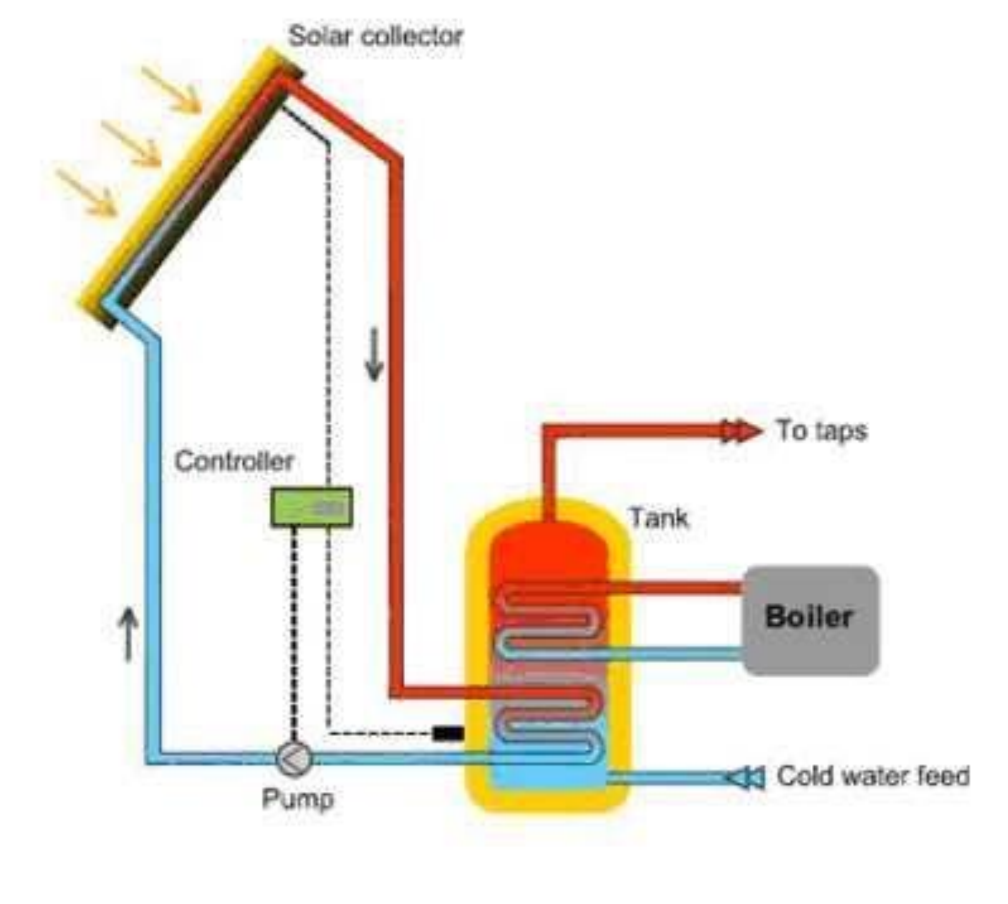






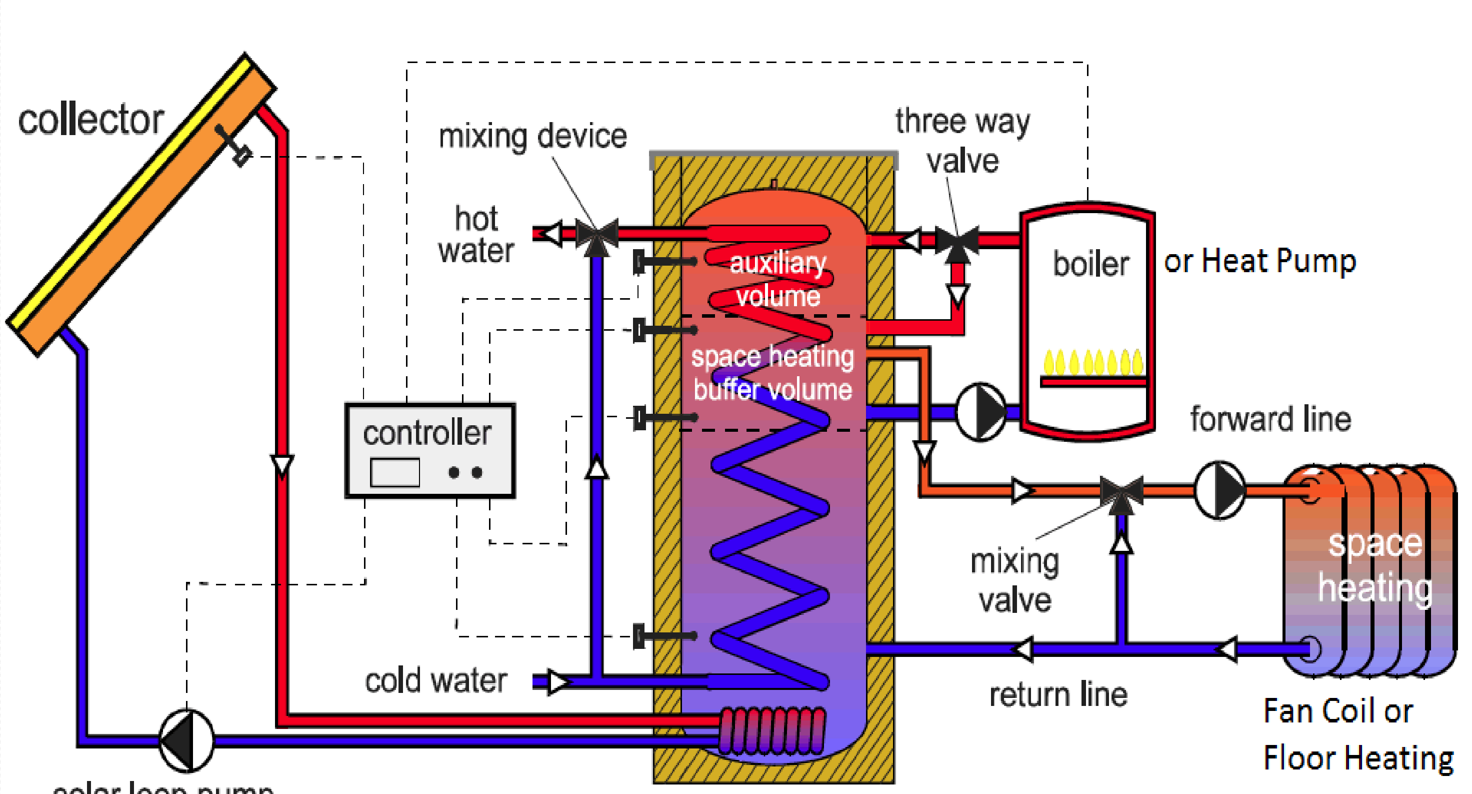
Solar thermal systems - planar collectors

- Water (or air) heating.
- Combination with auxiliary boiler (electric boiler, or gaseous or solid fuels).
- Efficient combination also with heat pump.



Solar thermal systems - planar collectors

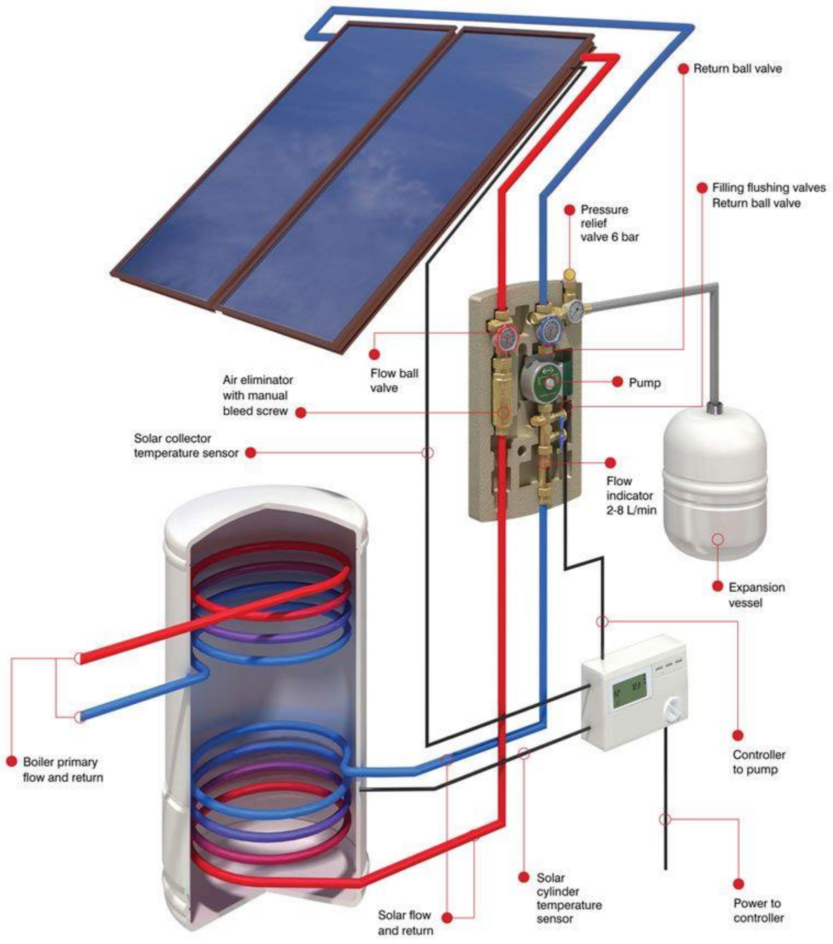
- Combined DHW heating + home heating support - variant with a longer payback period. (in winter, when most heat is needed, the least radiation is available).
- It is necessary to determine the collector area. A large area can mean a system overheating in summer - a pool heating option.



New4Old - Work Package 4.1 Technical Guidance for building designers 2009

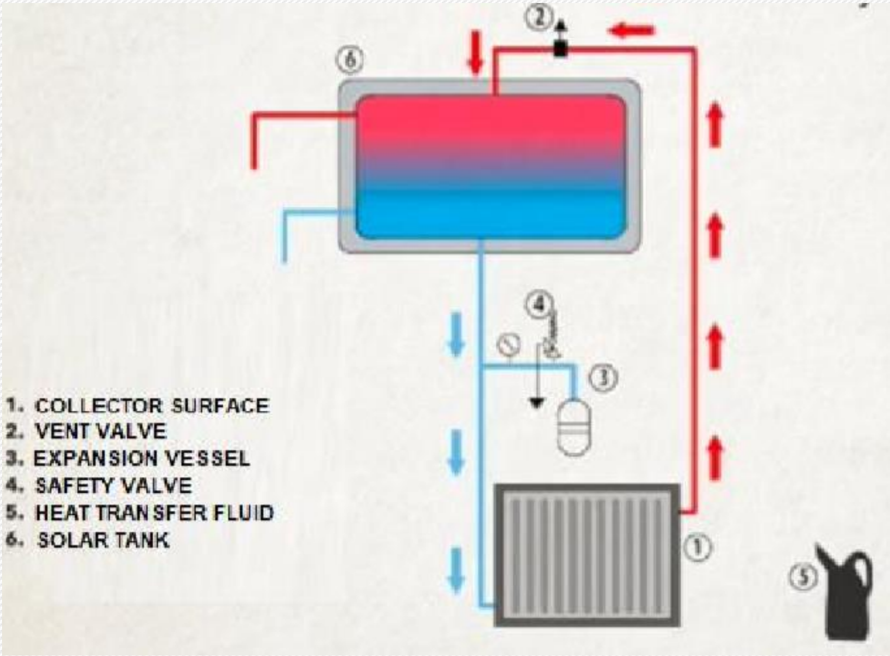
Solar thermal systems - planar collectors

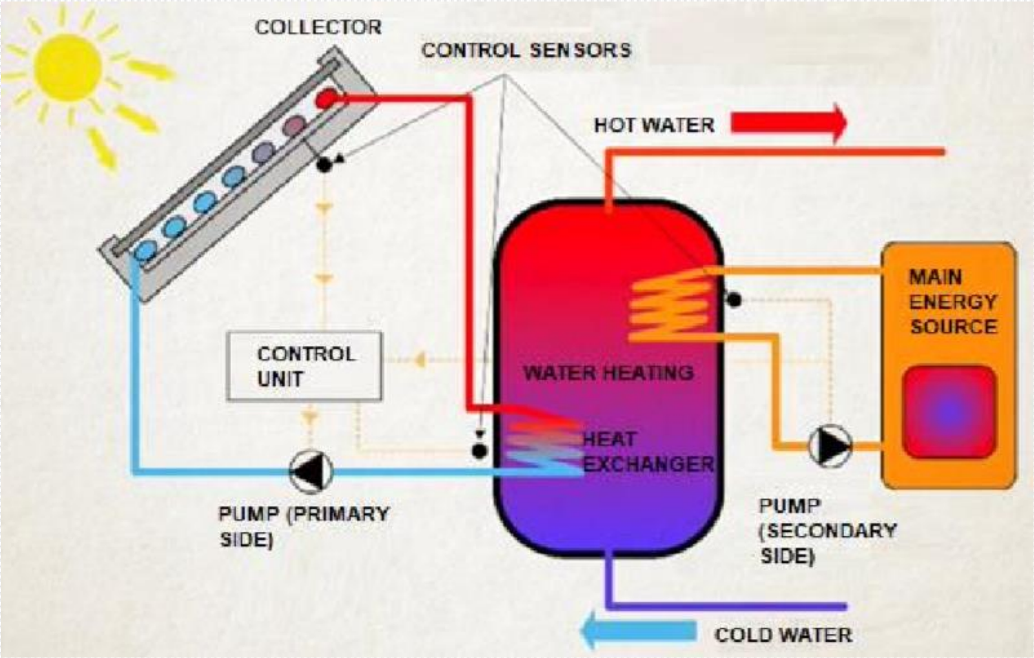
- The expansion vessel compensates for changes in the volume of water in the system caused by temperature changes (thus preventing the system from increasing pressure). Maintains system overpressure within required limits. Water expands due to volumetric expansion.



Solar thermal systems - plane collectors division

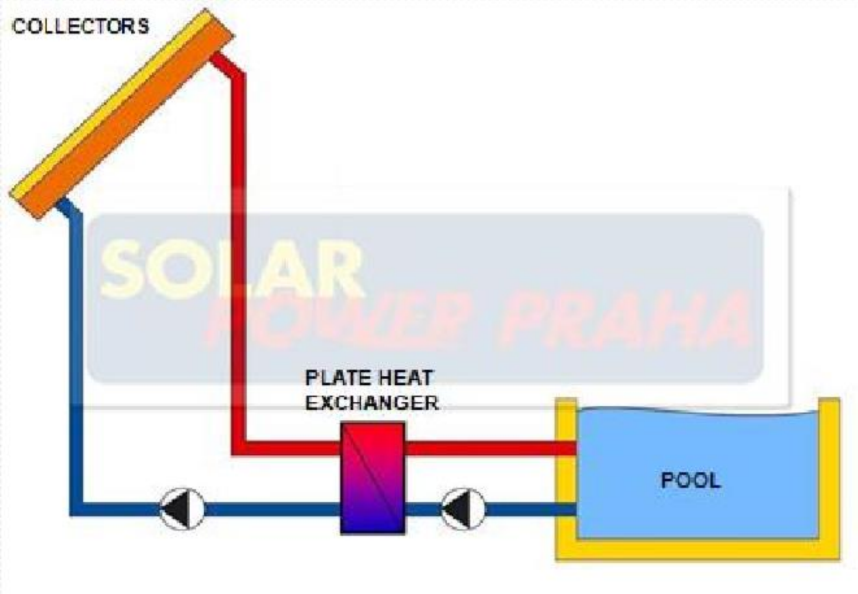
- According to heat transfer fluid - liquid / air
- According to circulation - gravity (boiler higher than collectors) / forced circulation (pump + regulation necessary)

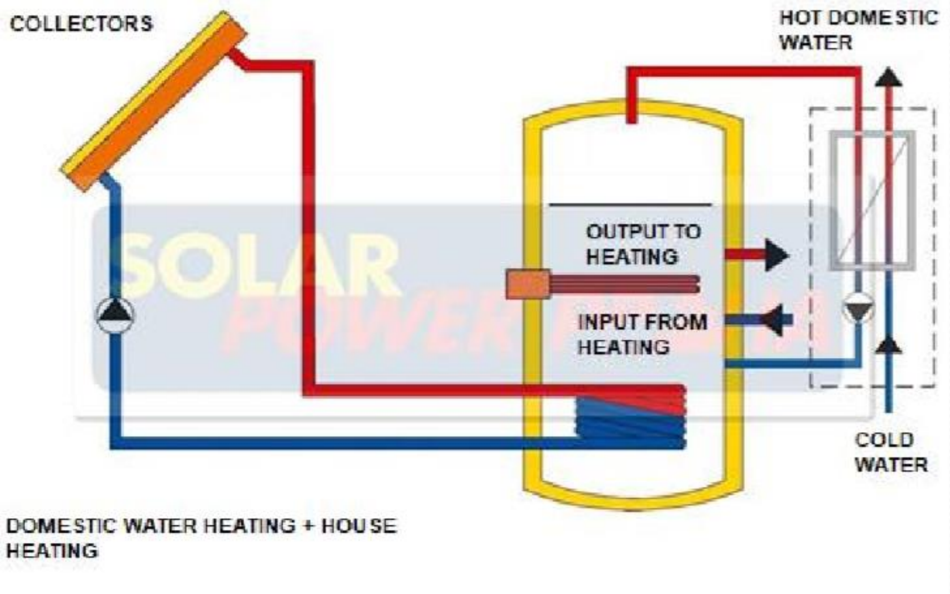




Solar thermal systems - plane collectors division

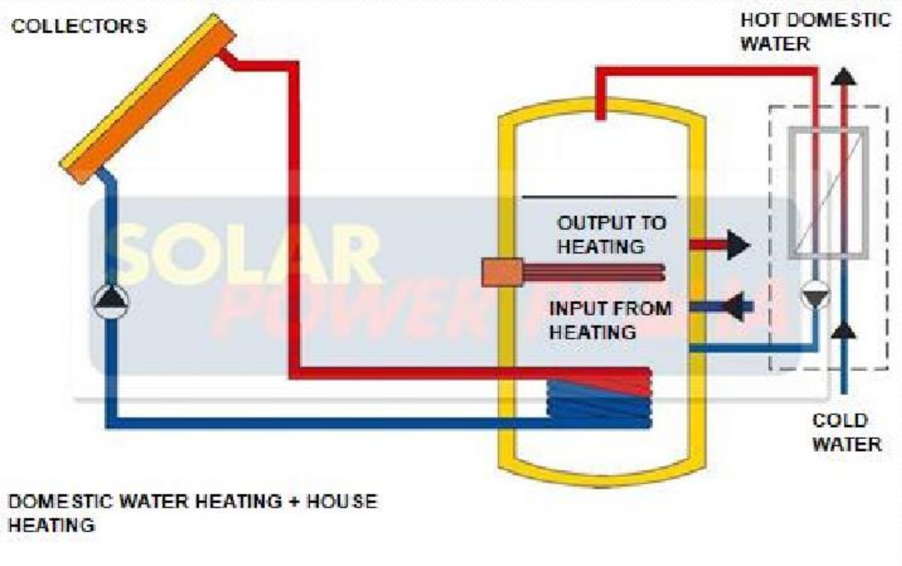
- According to the number of circuits - single-circuit (hot water in the pool) / double-circuit (hot water heating)
- According to operation - year-round (in Central Europe unfavorable + necessary to prevent freezing) / seasonal

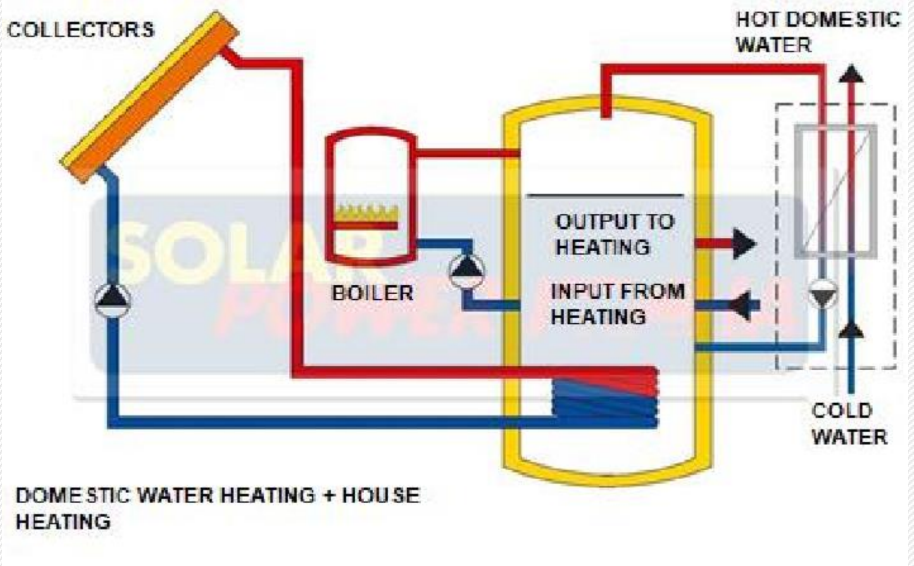




Solar thermal systems - plane collectors division

- According to the number of sources of heat supplied - monovalent / combined (heating with an electric coil or boiler (solid fuel, gas, electric boiler or heat pump))
- Types of collectors according to design:
  - flat (thermal)
  - flat (vacuum)
  - tubular (vacuum)

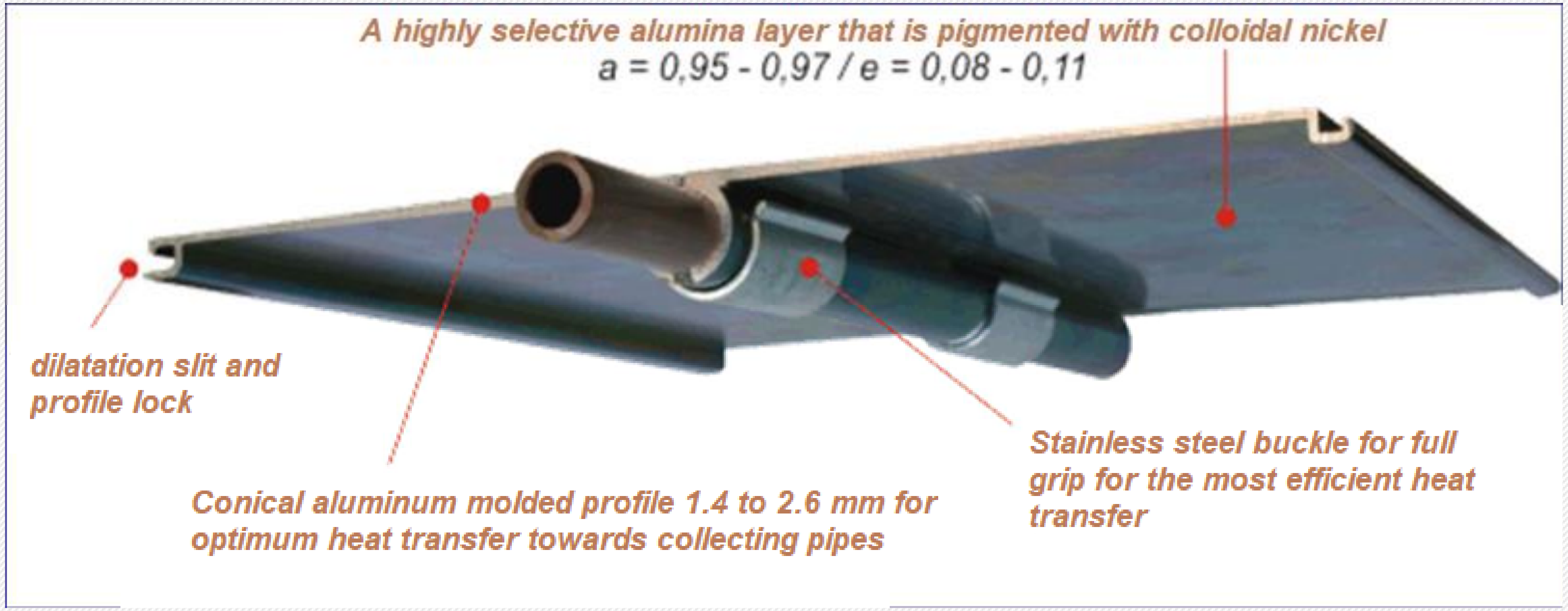




Solar thermal systems - plane collectors

Parts of the heat system:

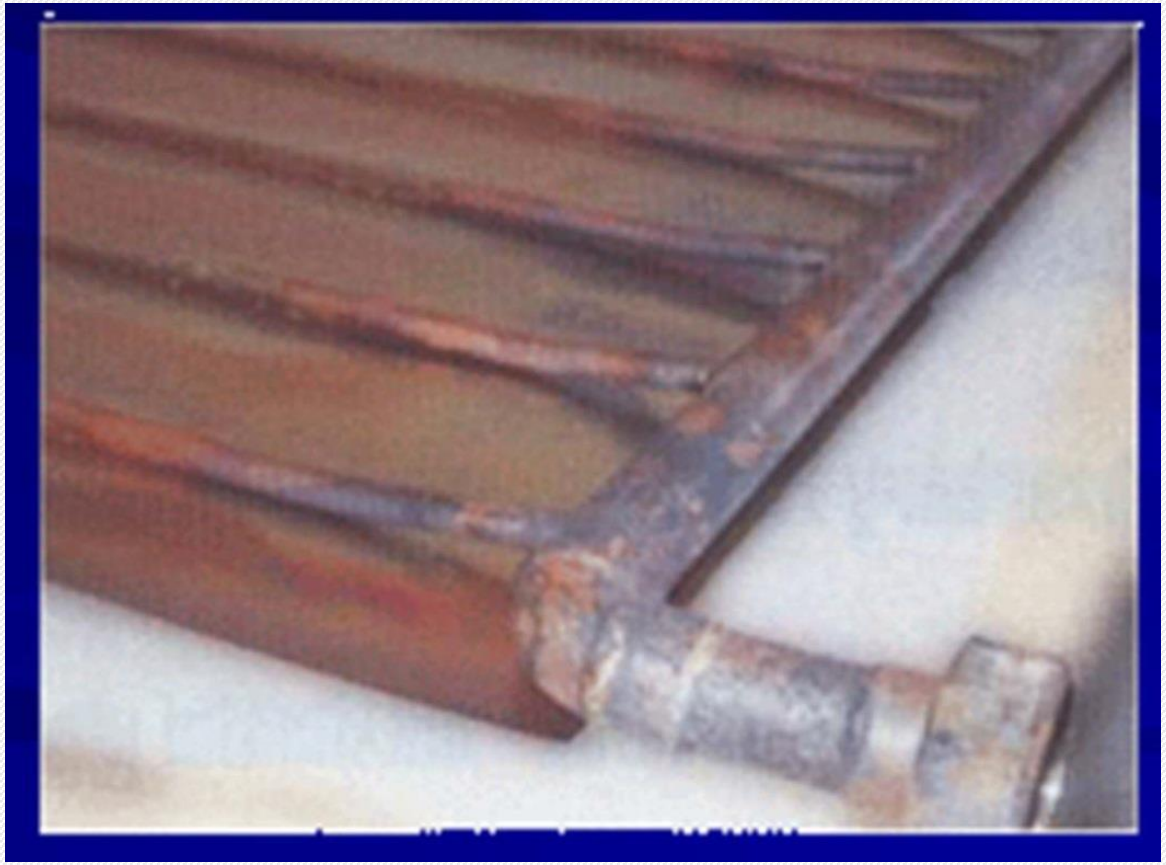
- **Absorber** - absorbs radiation, maximum absorption (min. 95%), minimum emissions (max. 5%), Cu, Al + selective layer enhancing absorption ($TiNO_x$, Al_2O_3), good thermal conductivity, large heat transfer surface, good connection to pipes ensuring the required heat transfer



Solar thermal systems - plane collectors

Parts of the thermal system:

- **Pipe construction** - thin copper pipe with good heat transfer. Mostly in the shape of H or U.



Solar thermal systems - plane collectors

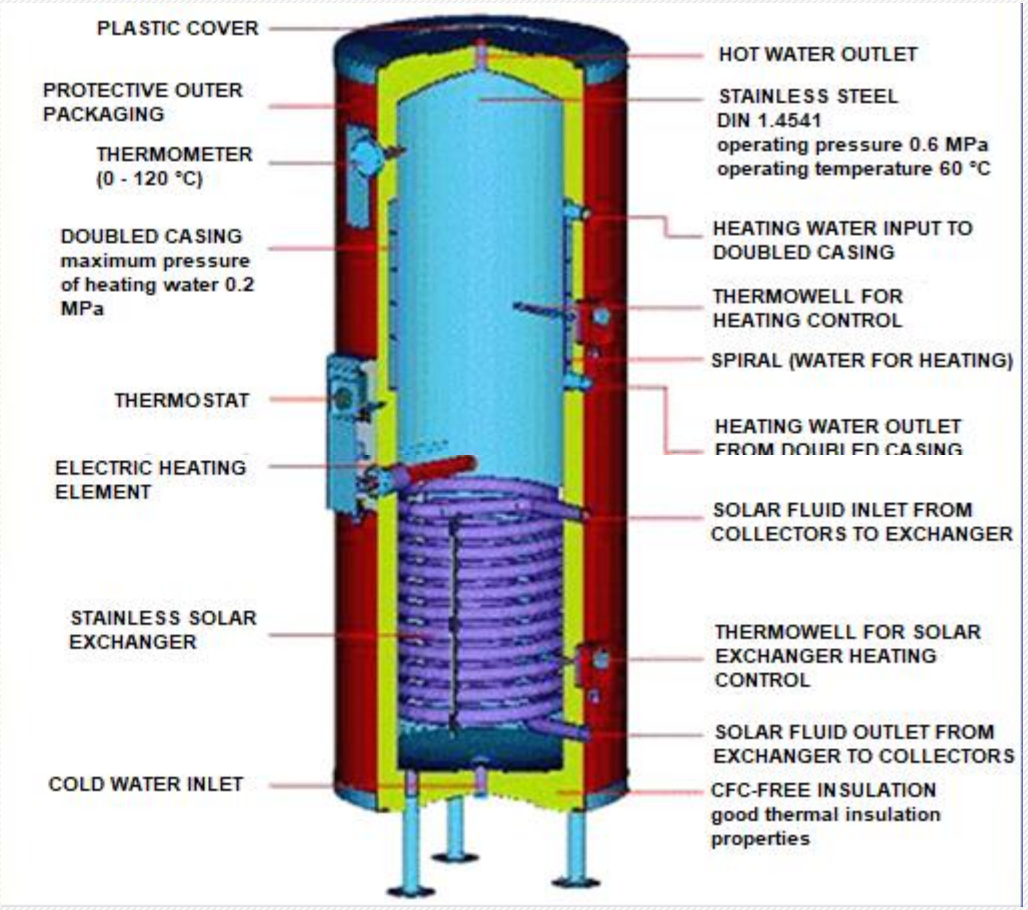
Parts of the thermal system:

- Heat transfer medium - solar liquid, water, corrosion inhibitors, antifreeze = necessary separate circuits (AGRIMEX, VELVABA, FRIDEX - toxic substances)
- Fittings - Copper pipes ensure a temperature drop between collector and heat exchanger by max. 1 °C
- Pumps - 220V, 12V - solar + regulation (venting, draining), insulation
- Expansion vessel - compensates thermal expansion of water

Solar thermal systems - plane collectors

Parts of the heat system:

- Solar storage (boiler) - heat accumulation, over-dimensioning, layering (standing boiler has better layering and slower cooling), adding heat source (electric heating element, solid fuel combustion), solar boilers are larger than conventional (100, 200, 300, 400 l).

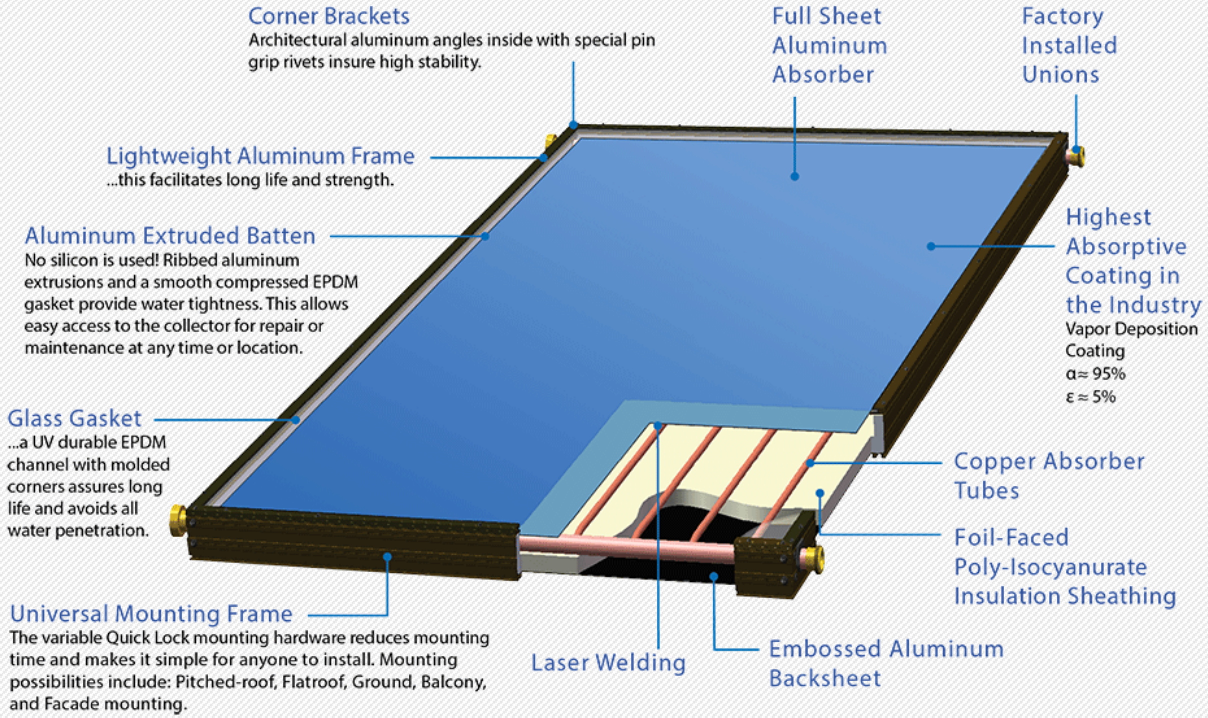


Solar collectors - design variants

Solar collectors		
Accumulation	Flow-through	
flat (thermal)	flat (thermal)	tubular (vacuum)

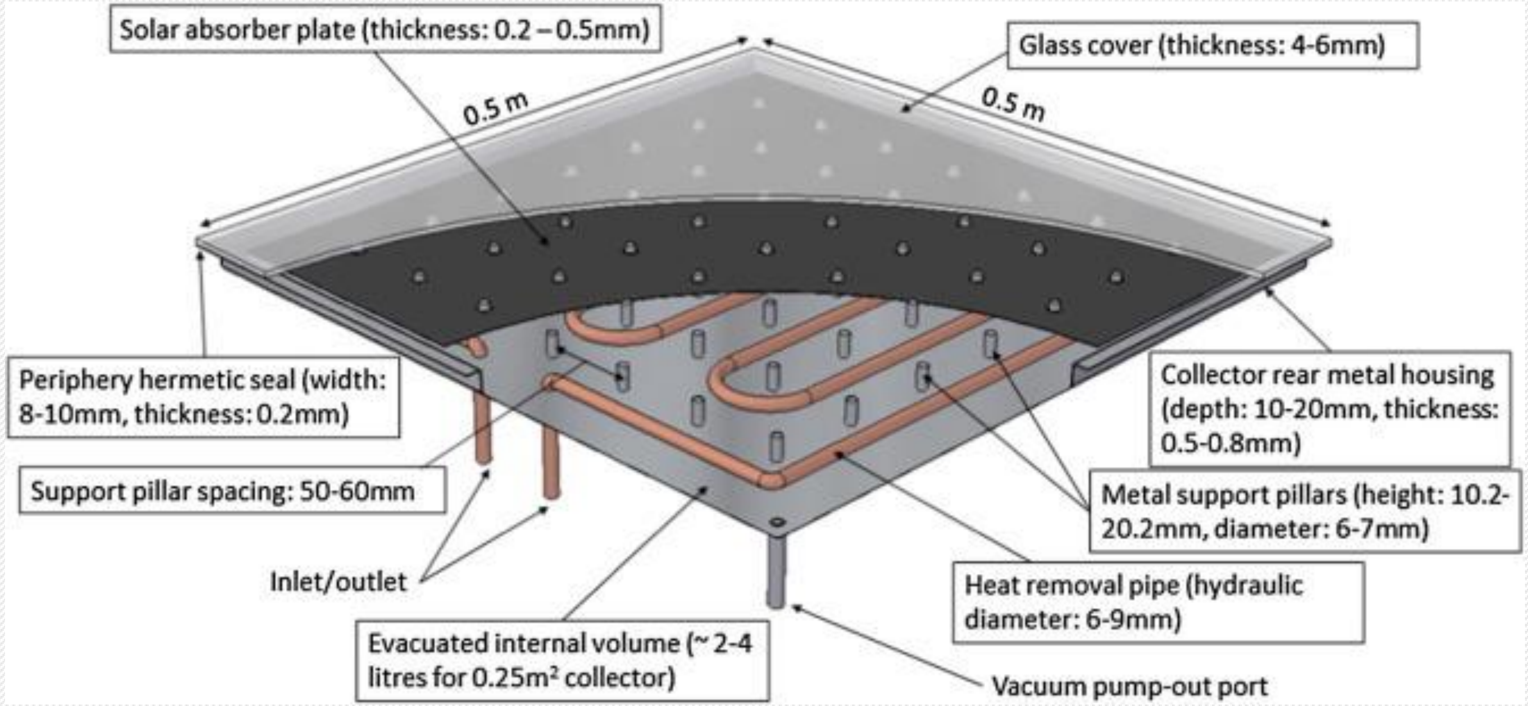
Flat collector - thermal

- The base is a load-bearing bath - a frame made of aluminum or stainless steel. Glass or mineral wool insulation.
- The absorber is provided with a selective surface and a solar glass (hardened (3-4 mm) - higher strength and colorless - higher throughput approx. 92%).
- Equipped with dilatation frame to prevent moisture penetration and anti-condensation ventilation system.



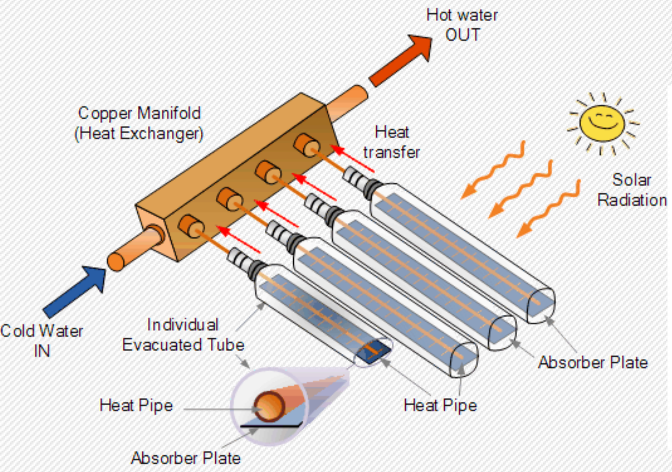
Flat collector - vacuum

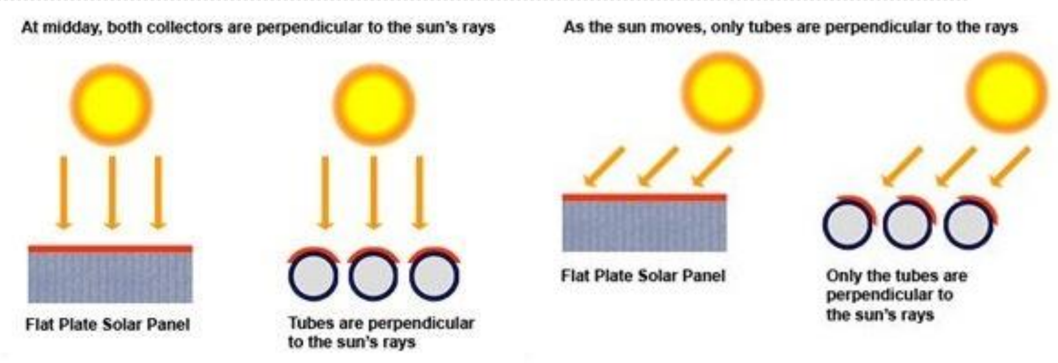
- Similar to thermal with the exception that the solar glass is equipped with supporting pillars - a vacuum of 10^{-3} Pa is created under the glass.
- Demanding on service, high price (therefore not much used in practice).

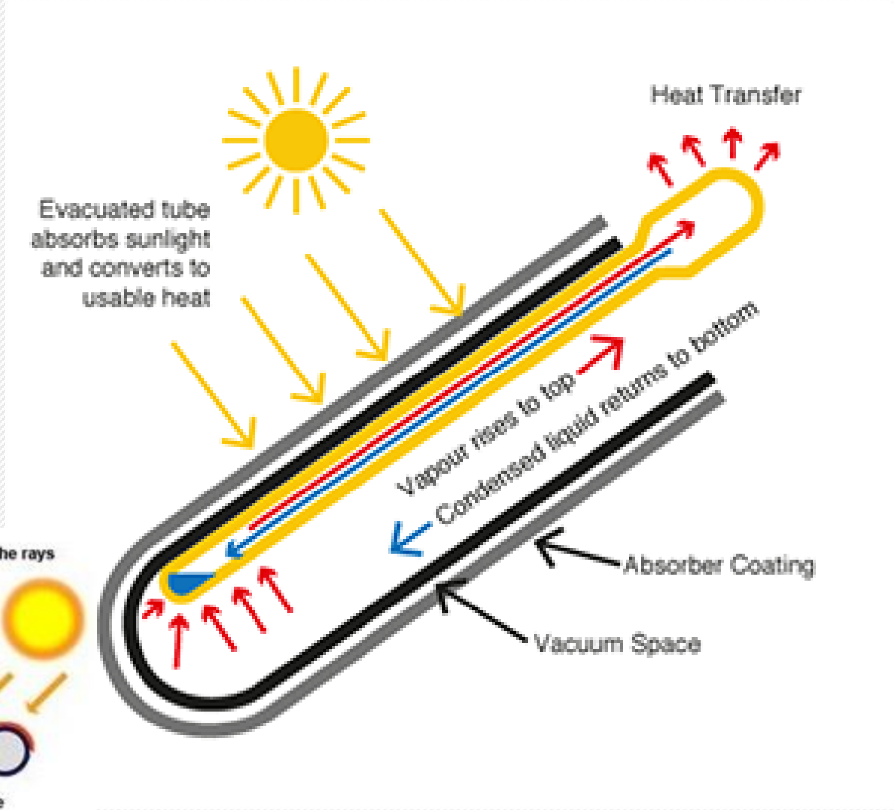


Tube collector - vacuum

- Glass tubes fixed and insulated.
- The solar glass has a selective surface.
- The tubes are inclined to allow steam to rise.
- More consistent efficiency during the year and during the day, but in summer it can be lower than that of a flat collector.

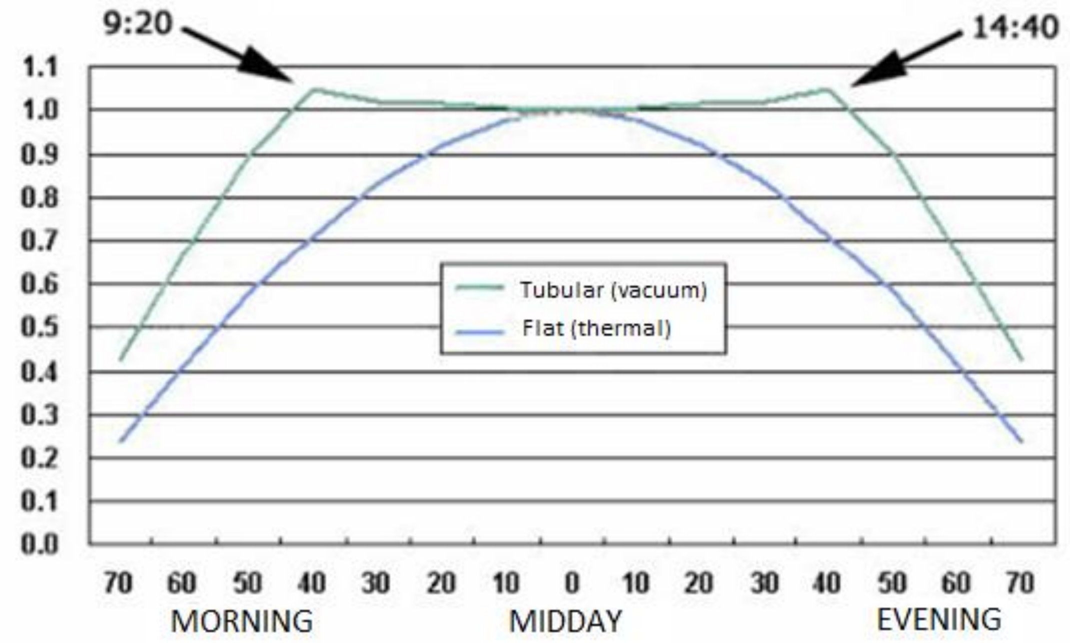




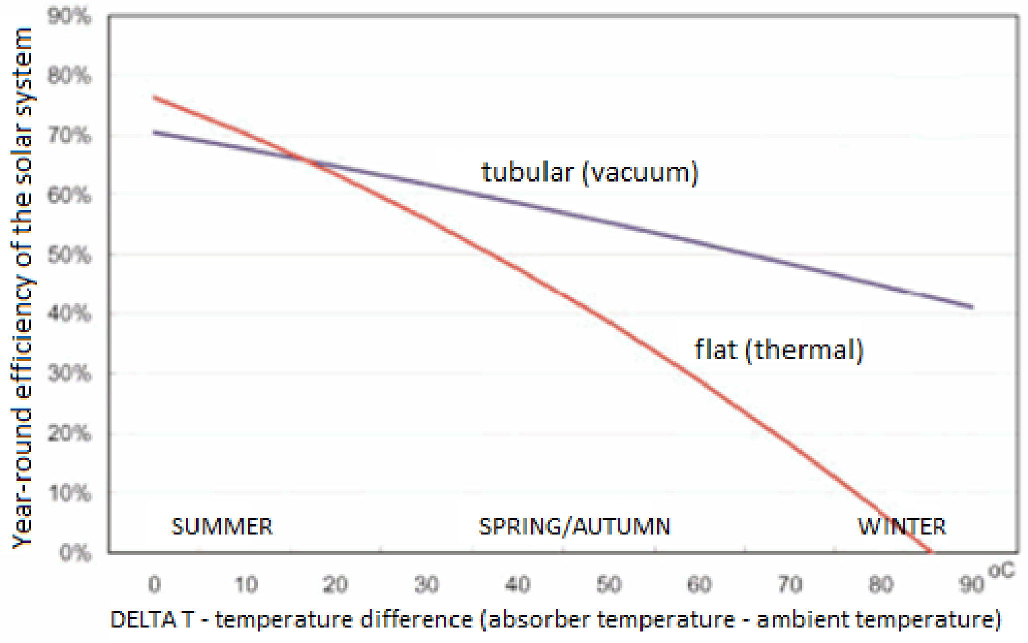


Comparing different types of collectors in terms of performance and efficiency

POWER OF COLLECTORS DURING DAY

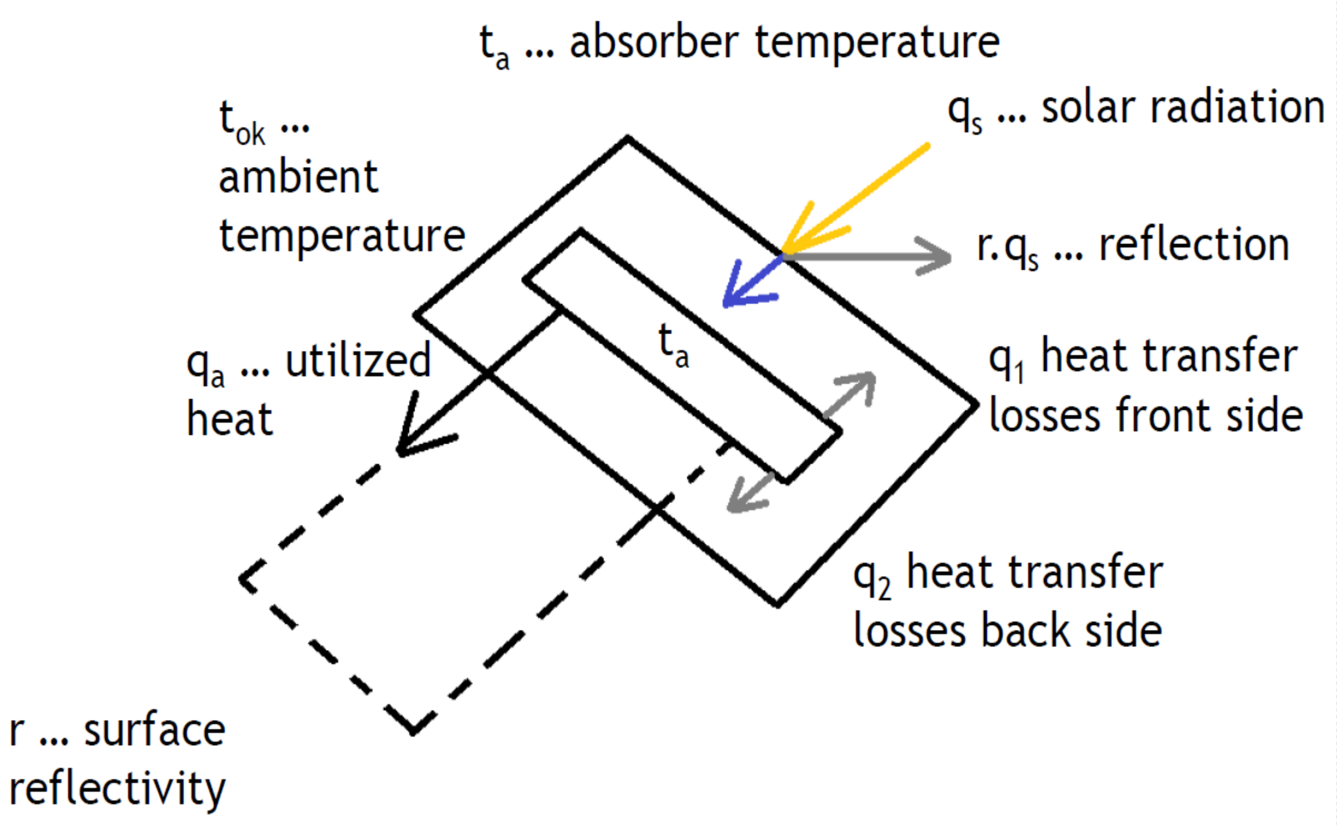


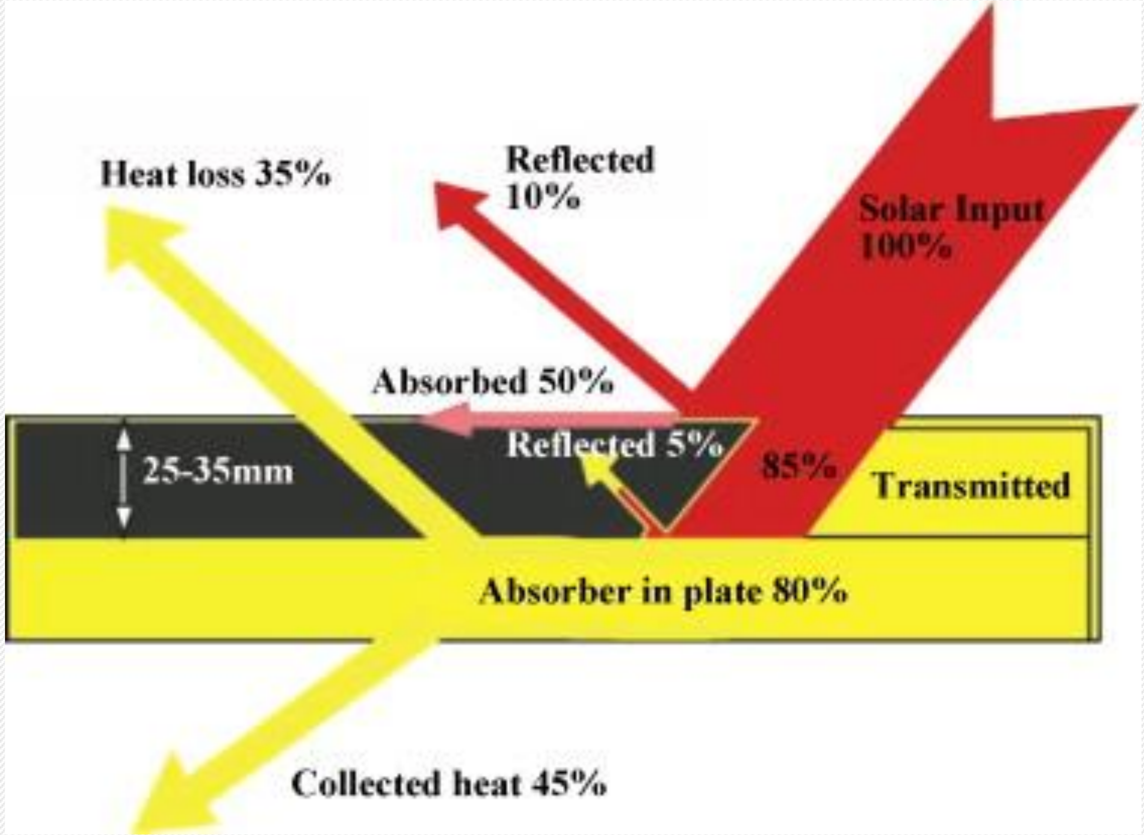
YEAR-ROUND EFFICIENCY OF SOLAR SYSTEMS



Collector efficiency depends on radiation intensity (efficiency increases with higher intensity), absorber absorption (efficiency increases with higher absorption) and ambient temperature, respectively temperature difference of absorber and environment (efficiency decreases with higher temperature difference)!

Collector heat balance





Collector heat balance (external)

$$(1-r)\cdot q_s = q_a + q_1 + q_2$$
$$(1-r)\cdot q_s = q_a + k_1\cdot(t_a - t_{ok}) + k_2\cdot(t_a - t_{ok})$$

$$q_a = (1-r)\cdot q_s - k_1(t_a - t_{ok}) - k_2\cdot(t_a - t_{ok})$$

$$q_a = (1-r)\cdot q_s - \underbrace{(k_1 + k_2)}_{k}\cdot(t_a - t_{ok})$$

$$\eta = \frac{q_a}{q_s} \quad \Rightarrow \quad \eta = (1-r) - \frac{k\cdot(t_a - t_{ok})}{q_s}$$

A mathematical expression called reduced temperature - characterizes external influences ($q_s \approx I_s$)

- $q_1 + q_2$ = heat transfer losses at the back and front of the collector => k_1 - heat transfer coefficient front, k_2 - heat transfer coefficient back
- Heat loss through conduction, convection and radiation (q_v+q_p+q_z)
- The efficiency of the collector depends on the intensity of the radiation, the ambient temperature (or the temperature difference) and the absorber absorption.
- If the temperature difference is zero, the collector achieves the highest efficiency, the higher the temperature difference, the lower the efficiency.
- The heat loss increases with a 4-square temperature difference. Loss Reduction: Cover glass reduces radiation losses, vacuum reduces flow losses and thermal insulation reduces conduction losses.

Links to investigate

- https://www.youtube.com/results?search_query=solar+thermal+collector
- https://www.youtube.com/results?search_query=domestic+solar+heating
- or google it…

Possibilities of converting solar radiation into electricity – photoelectric effect

- Irradiation of some substances causes their charging - metals (Zn + UV radiation), semi-metals (Si + visible radiation), organic compounds.
- Short wavelengths absorbed => electron emission, long wavelengths remain in spectrum - photoelectric effect does not occur.
- Electron energy should depend on the intensity of the radiation, but experiments have shown that the energy of the photons depends only on the frequency f:

$$E = h \cdot f$$

h … Planck's constant ($6{,}63.10^{-34}$ J.s)

- Every substance has a threshold frequency - for frequencies below this frequency there is no emission of electron, for frequencies above this frequency the emission of electron occurs!

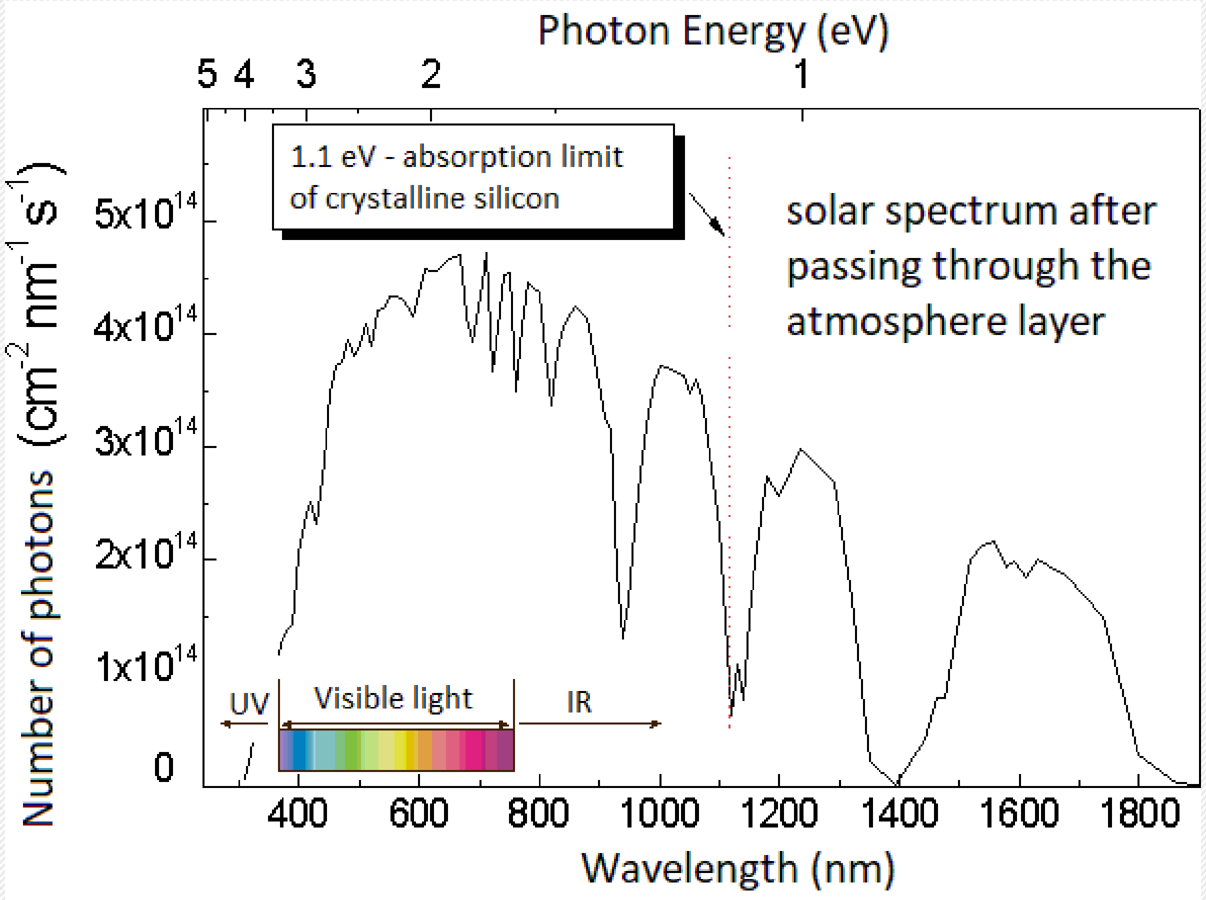
Photoelectric effect

- The emission of an electron is due to the absorption of one quantum of a photon with a certain energy => the photon ceases and transmits its energy to the electron.
- The energy is then partly used to escape the electron from the crystalline lattice (output work *A*) and the rest is converted to its kinetic energy E_{kin} or energy loss ΔE, according to the law of energy conservation:

$$h \cdot f = A + \Delta E + E_{kin}$$

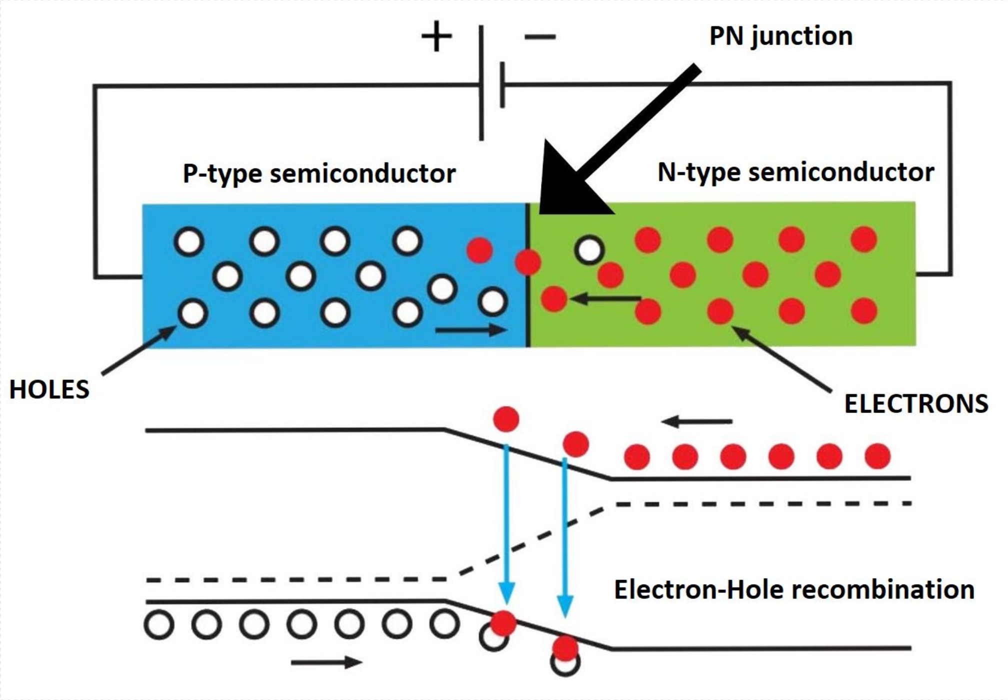
Absorption limit of crystalline silicon

- Silicon PV cells use visible radiation and infrared radiation with a wavelength shorter than 1100 nm => photon energy of at least 1.1 eV.



Photovoltaic cells - internal photoelectric effect

- Electrons in semiconductors do not leave the crystal itself, only increase its conductivity.
- A photon with sufficient energy can release the electron from the valence to the conductive band in the semiconductor material. In its original place there is a so-called hole - elementary positive charge. If a PN junction is created in the semiconductor material, an electrical voltage is generated. When the electrodes are interconnected by an external circuit, the electrons travel to the opposite electrode, where they recombine with the holes and an electrical current passes through the external circuit.



Photovoltaic panels - materials

1. Silicon - the most widely used, efficiency in laboratory conditions up to 25%, mass production 15 - 20%.
   a) Monocrystalline - the oldest, most used, 90% of production.
   b) Polycrystalline – 5% of production.
   c) Amorphous - has no crystalline structure, other spectral sensitivity - works with diffuse radiation.
   d) Thin films - multilayer nanotechnology (material saving), thin layers of amorphous or microcrystalline silicon.
2. Other semiconductors - for example gallium arsenide, cadmium sulphide,…
3. Organic compounds - panels III. generation, cheaper but not yet powerful.

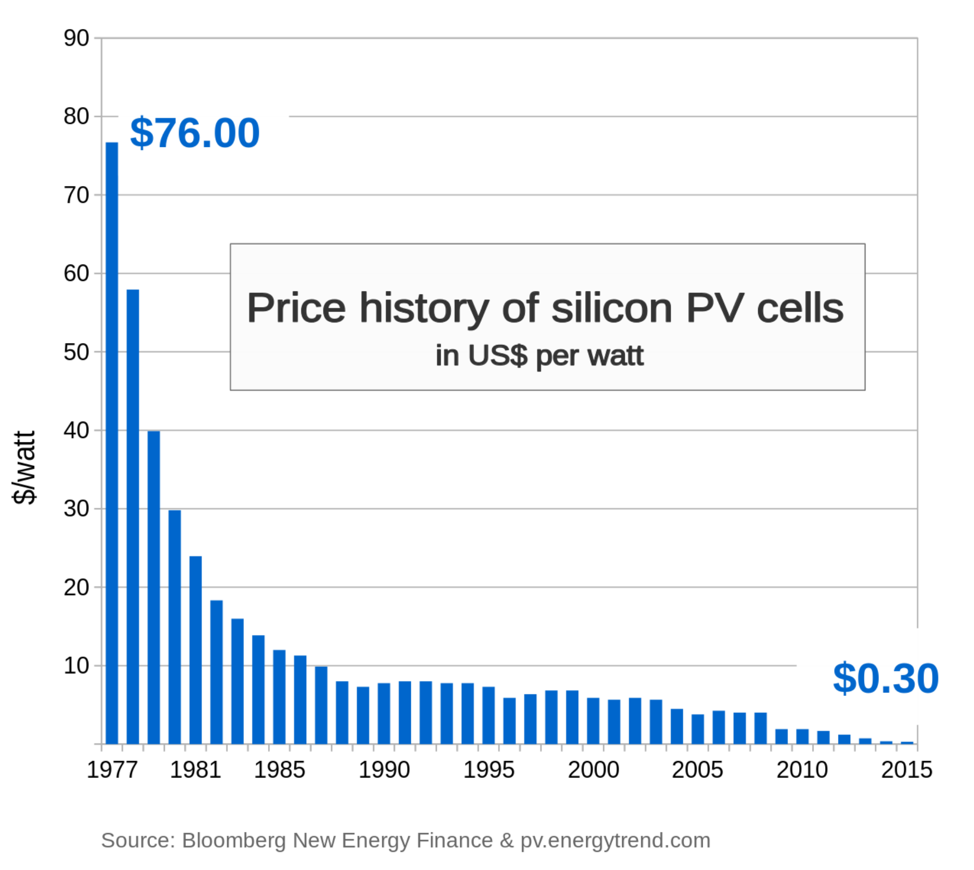
Degradation is reported for each panel - for example, according to the manufacturer, in 20 years the performance will drop by 10%. Amorphous silicon degrades faster (about 5 years).

Photovoltaic panel efficiency

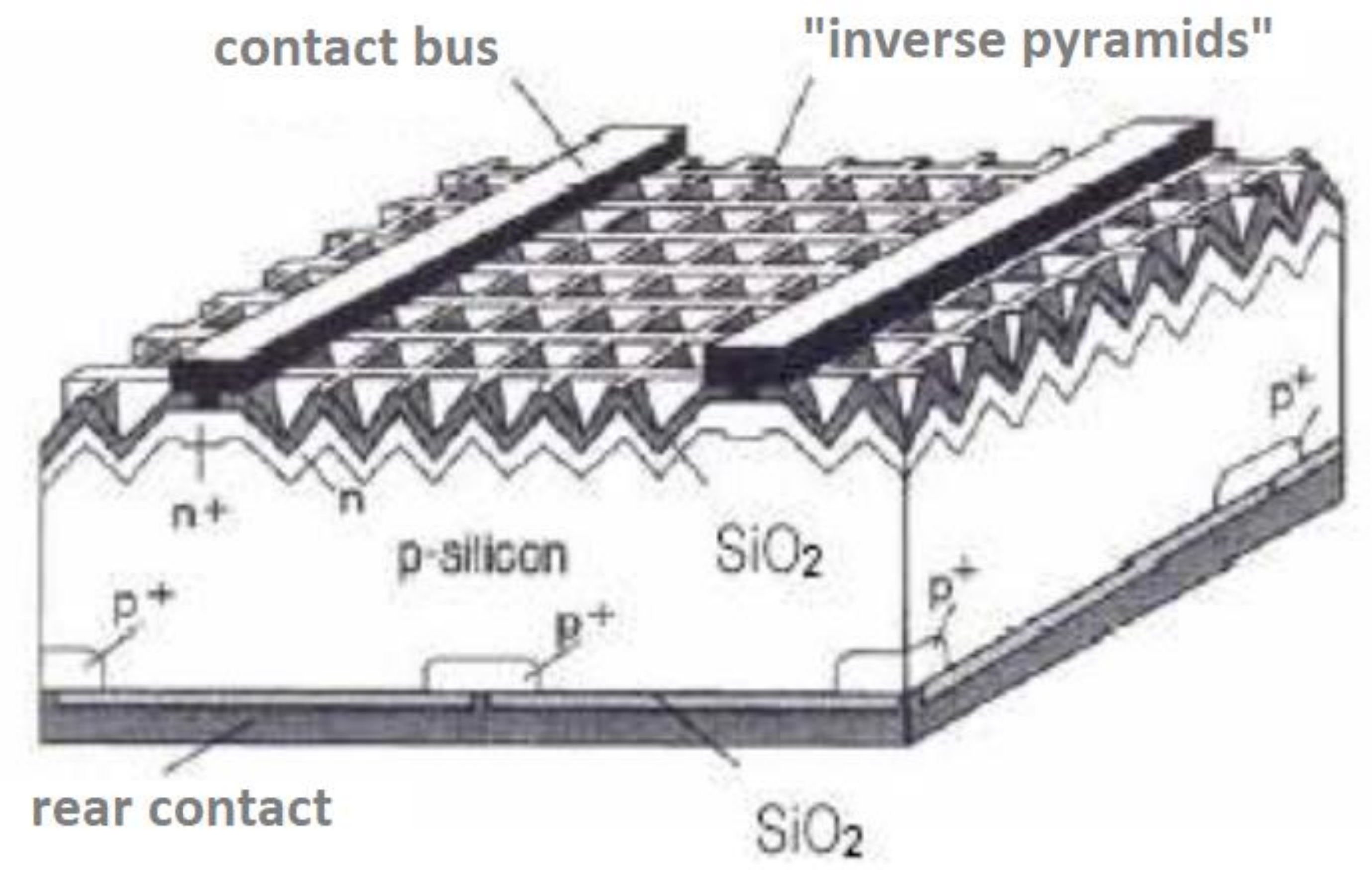
- The efficiency of the PV panel is defined as the ratio between the energy falling on the PV panel and the energy delivered to the load.
- The captured energy depends on the area of the PV module and its orientation towards the Sun.
  - About 1000 W/m^2 can be counted on the Earth's surface.
- Example: at an efficiency of 15%, a PV module with an area of 1 m^2 will deliver approximately 150 W.
- Efficiency alone is critical only for limited space installations (mobile and roof applications).
- The primary value for assessing the installation is the cost per unit of energy produced, including the cost of the entire system.

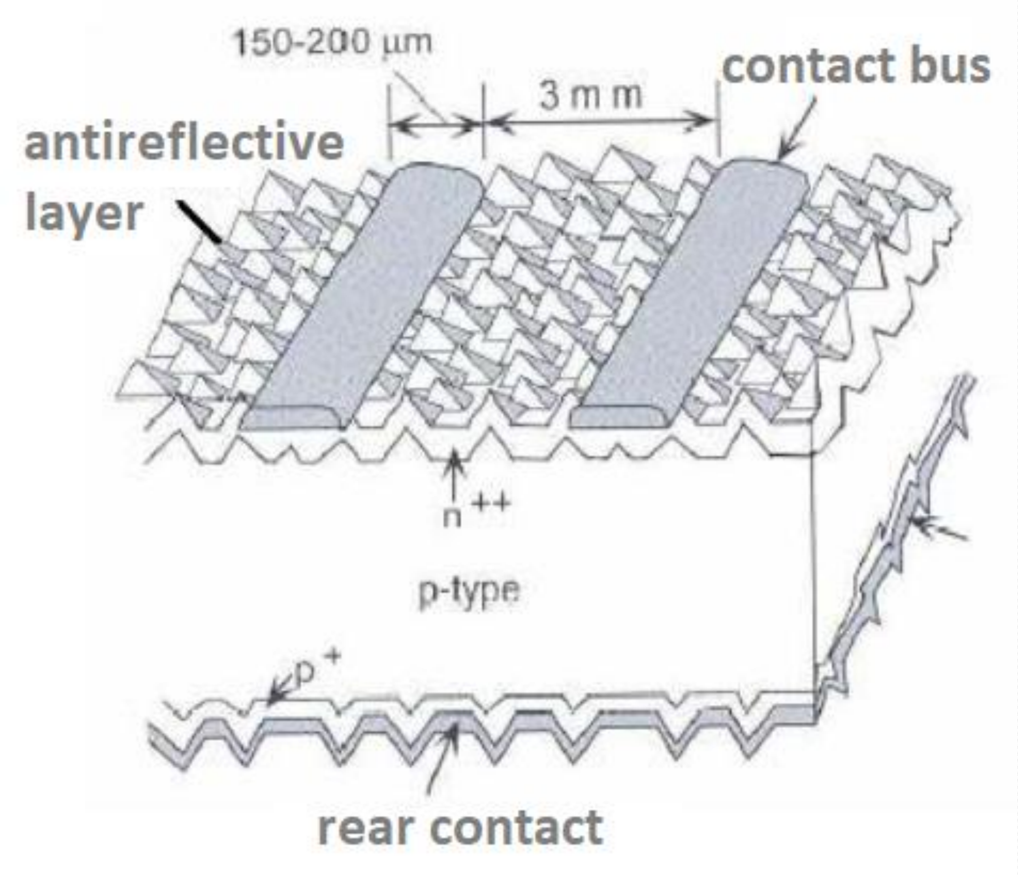
Silicon cells

- Silicon is non-toxic, available and stable (sandstone, granite, quartz). Managed technology, we can process.
- Silicon has a suitable width of forbidden zone - suitable radiation spectrum (silicon is compatible with it).
- The maximum theoretical efficiency of the Si cell is 32% (for 1 PN junction only) - Shockley-Queisser boundary, the residual energy cannot be used.



Silicon cells





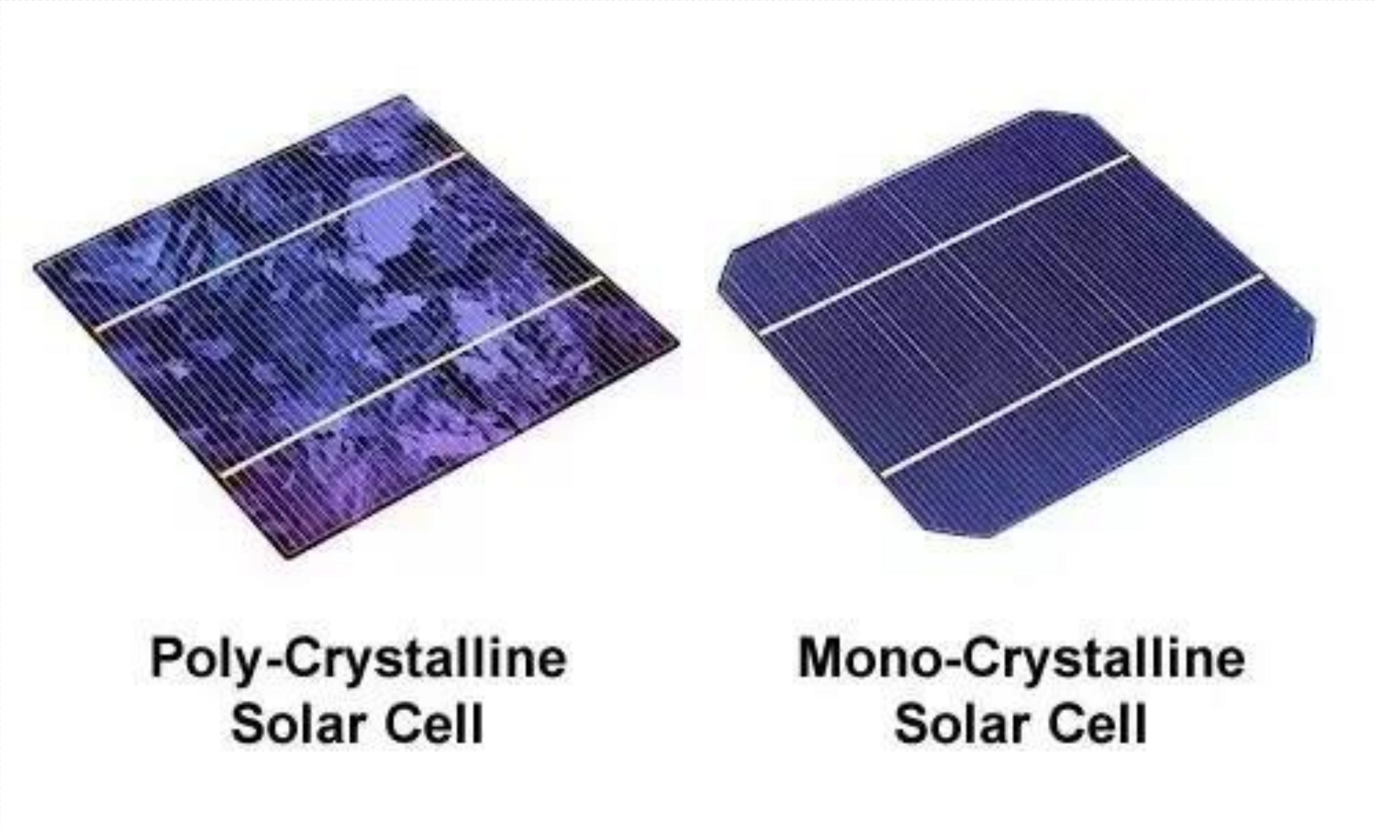
Photovoltaic cell production

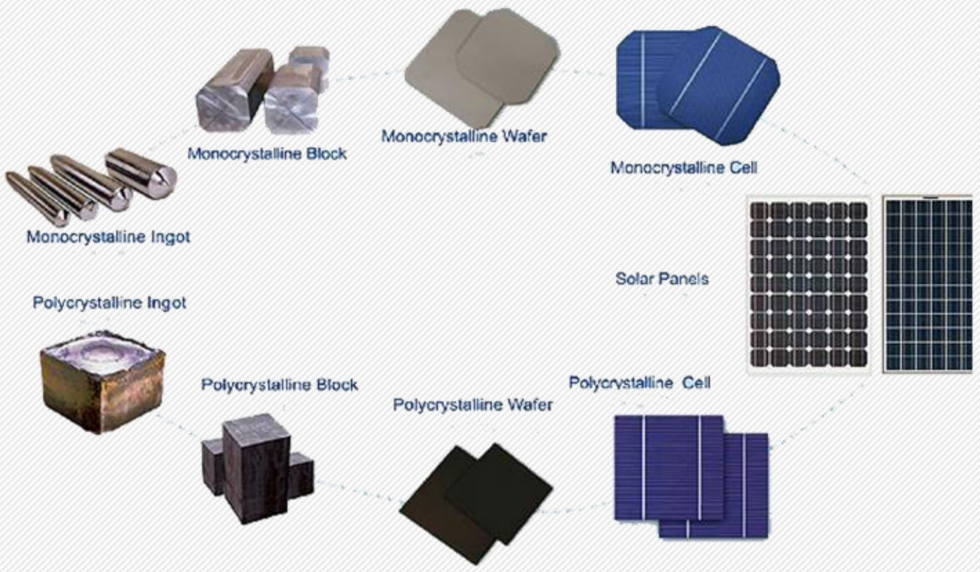
- Melting pure electrotechnical silicon from silicon sand -> obtaining Si ingot (purity Si 97 - 98%).
- Further, cutting into slices (wafers) - getting a plate.
- Smoothing, grinding, etching - PN junction infusion - the upper layer of plate is N and the basic substrate is P
- SiO_2 surface passivation -> etching structures - texturization - inverse pyramid is etched on the cell surface - the probability of photon absorption is increased.
- Applying a protective and anti-reflective layer - the thickness of the antireflective layer defines what wavelength will interfere, so how the cell will look colored. However, the larger the layer (the longer the deposition time) the worse the optical efficiency - the best optical efficiency is the blue color.
- Finally, the application of contacts should be as small as possible.

Monocrystalline vs. polycrystalline

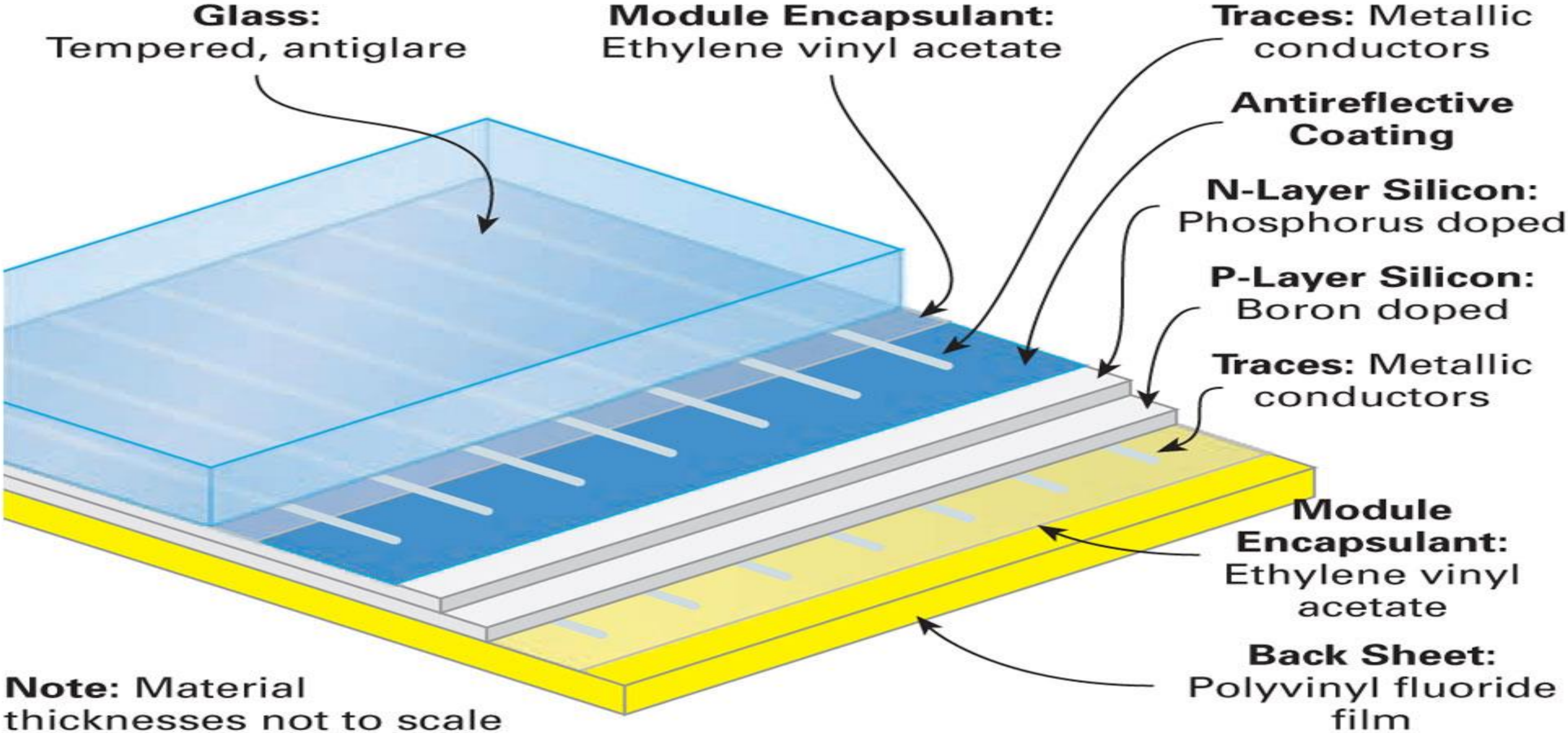
- Polycrystalline is cheaper, simpler, but has poorer conductivity at the crystal interface - less efficiency.
- Monocrystalline production is more demanding - the need for a uniform and very pure Si ingot. Furthermore, cutting takes place (obtaining wafers), resulting in a lot of unused waste material.
- To obtain a polycrystalline ingot of the same size, it is sufficient to crystallize a plurality of smaller Si crystals and then produce the substrate and compress it into one unit => high purity cannot be achieved, the transitions between the crystals are evident.

Monocrystalline vs. polycrystalline



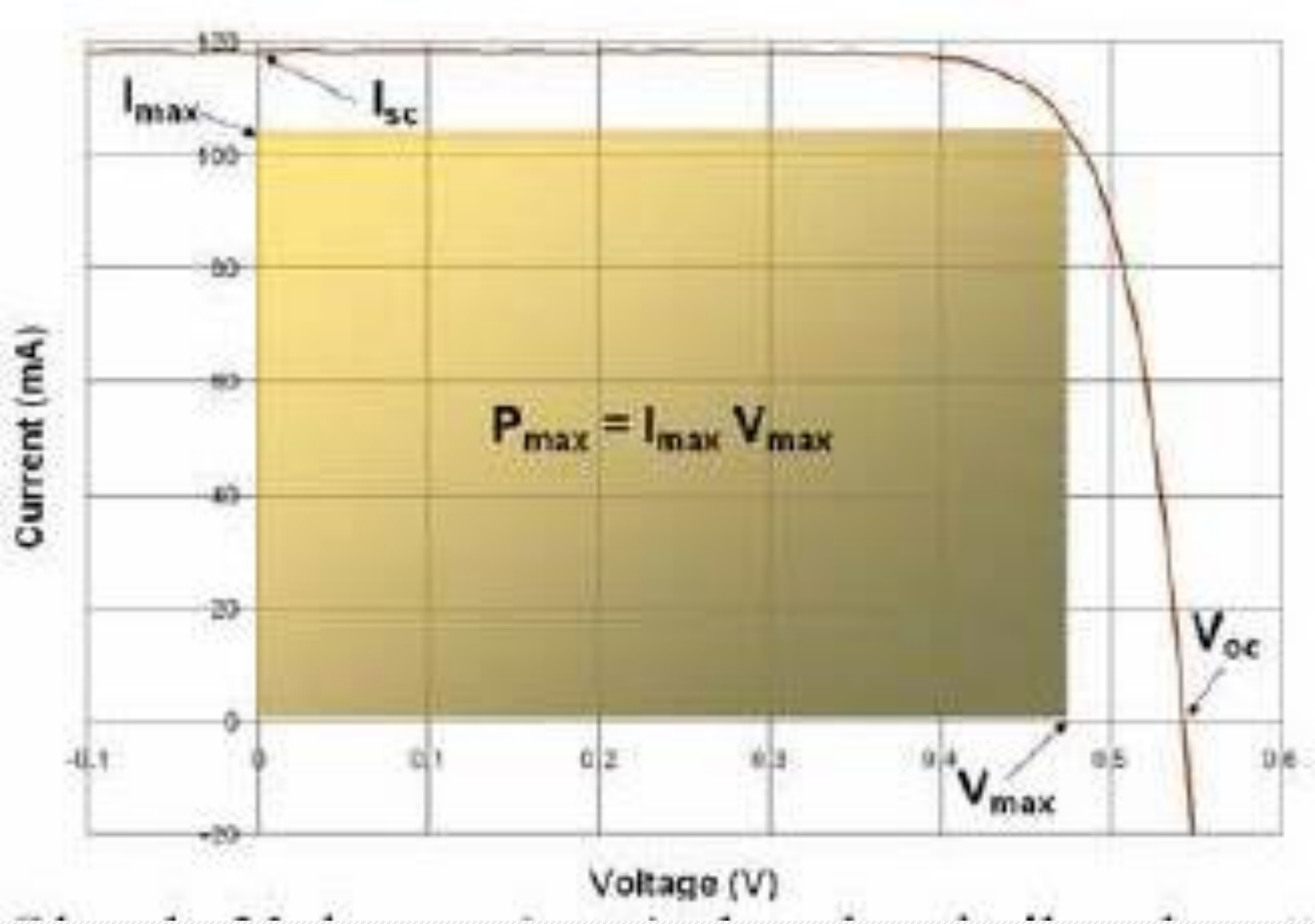


PV Module Anatomy



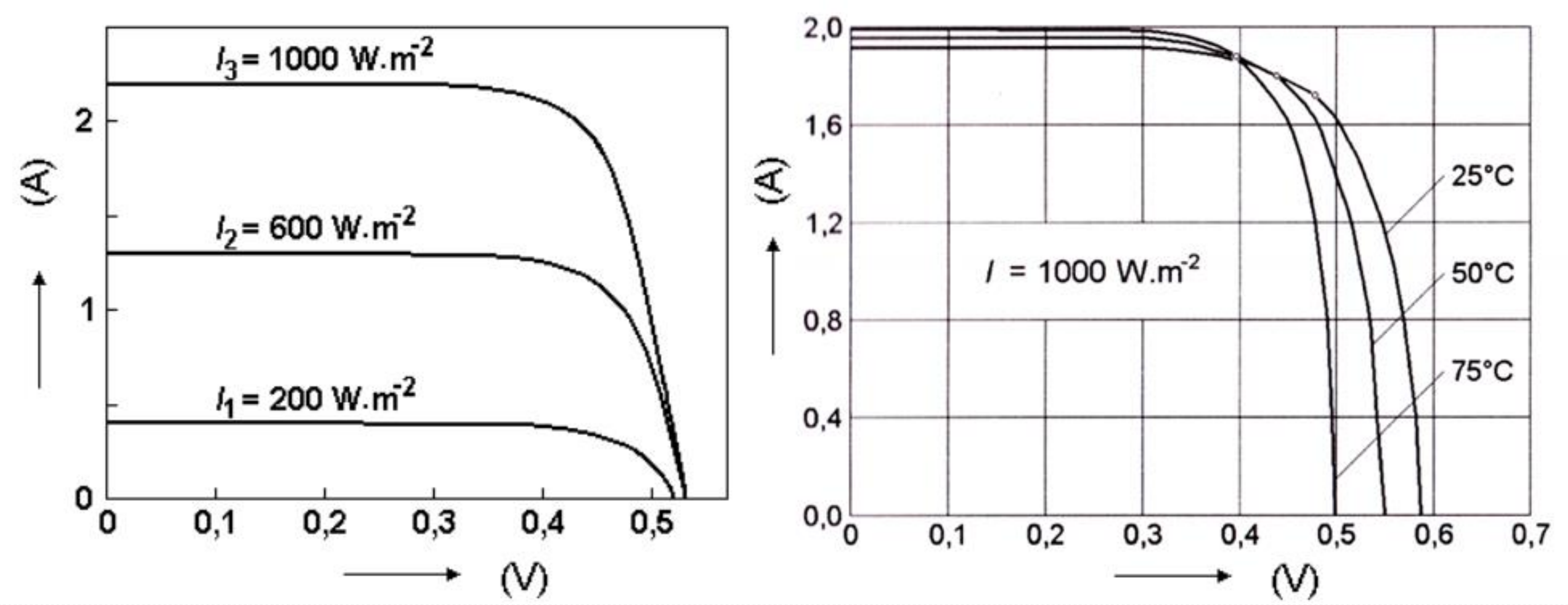
Note: Material thicknesses not to scale

VA Characteristics of a PV cell



- V_{oc} … defines material
- I_{sc} … defines the cell size
- The characteristic further defines the series and parallel resistance of the cell.

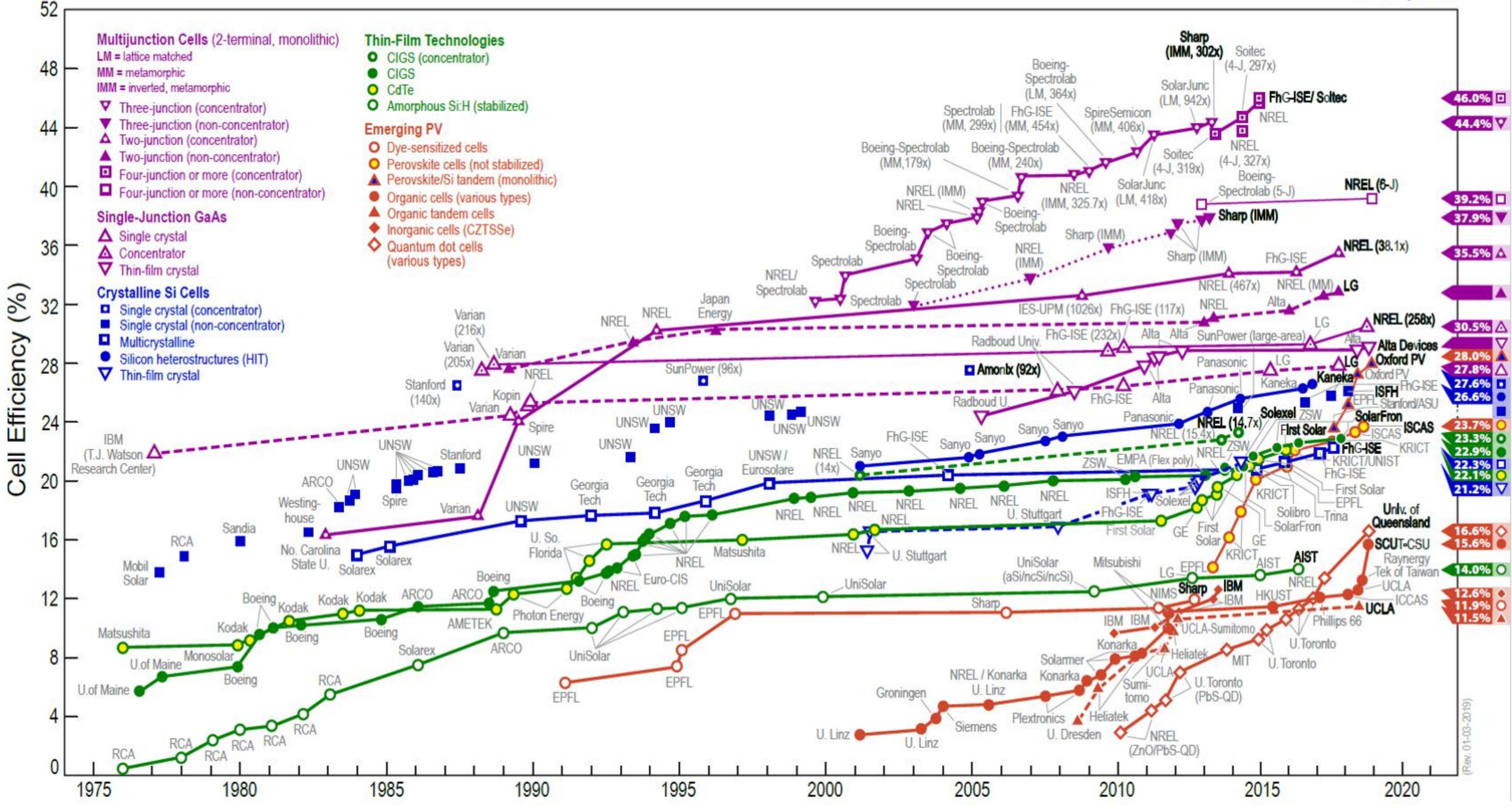
VA characteristics of the PV cell



As the temperature rises, the efficiency decreases and the delivered power decreases!

Best Research-Cell Efficiencies

NREL Transforming ENERGY

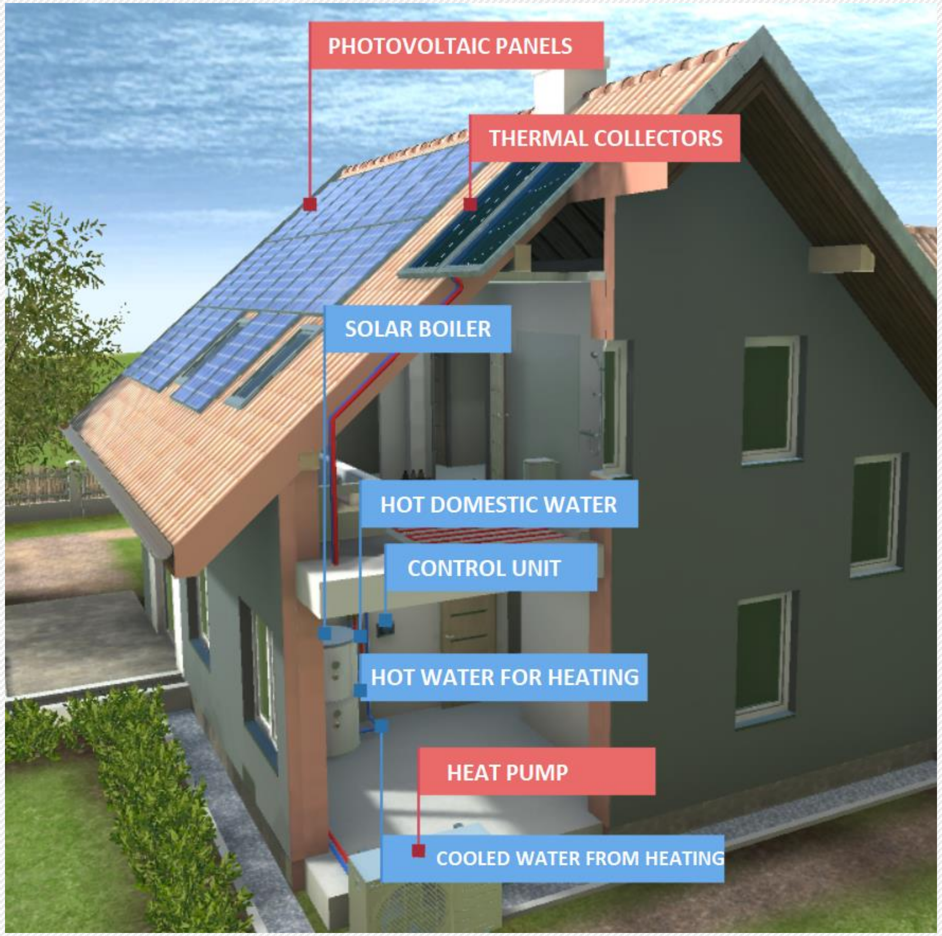


Links to investigate

- https://www.youtube.com/results?search_query=photoelectric+effect
- https://www.youtube.com/results?search_query=photovoltaic+panels
- https://www.youtube.com/results?search_query=photovoltaic+cells
- or google it…

Low-power installations

- These are mainly domestic (roof) sources of electricity and heat. The position and orientation of solar panels regardless of type (thermal or photovoltaic systems) is essential in this case.
  - The ideal case is to position the panels by means of a tracking mechanism so that sunlight falls perpendicular to the panel throughout the whole day. However, this is costly and regulatory-intensive, and therefore very little used in domestic applications.
  - If the positioning mechanism is not available, then in the northern hemisphere it is best to orient the panels to the south (southeast to southwest) under a slope of approximately 45° - 50°. If the slope is less than 15°, the panels lose their self-cleaning ability.



Domestic photovoltaic applications

- Photovoltaic panels are currently available in power ranges from 270 Wp to 300 Wp (Watts in peak). The area of one panel is usually about 1.65 m^2.
- The maximum power output of a domestic photovoltaic power plant is primarily a matter of the country's legislation.
  - Example: in the Czech Republic, the maximum capacity of a domestic PV plant does not exceed 10 kWp, because the operator is not obliged to hold a license (energy trade license) within this limit. This limit also applies to income tax exemptions if you supply unused electricity to the grid. Finally, this limit is set in the conditions for obtaining state subsidies for the construction of a domestic PV source.

Trouble with domestic PV plants

- The main problem is uneven production and consumption of electricity. While morning and evening household consumption is highest, the plant does not produce any electricity. During the day when the plant is running at full power, consumption is low. These fluctuations can be solved either by installing an accumulation system or by using Net-metering.

Storage systems for households

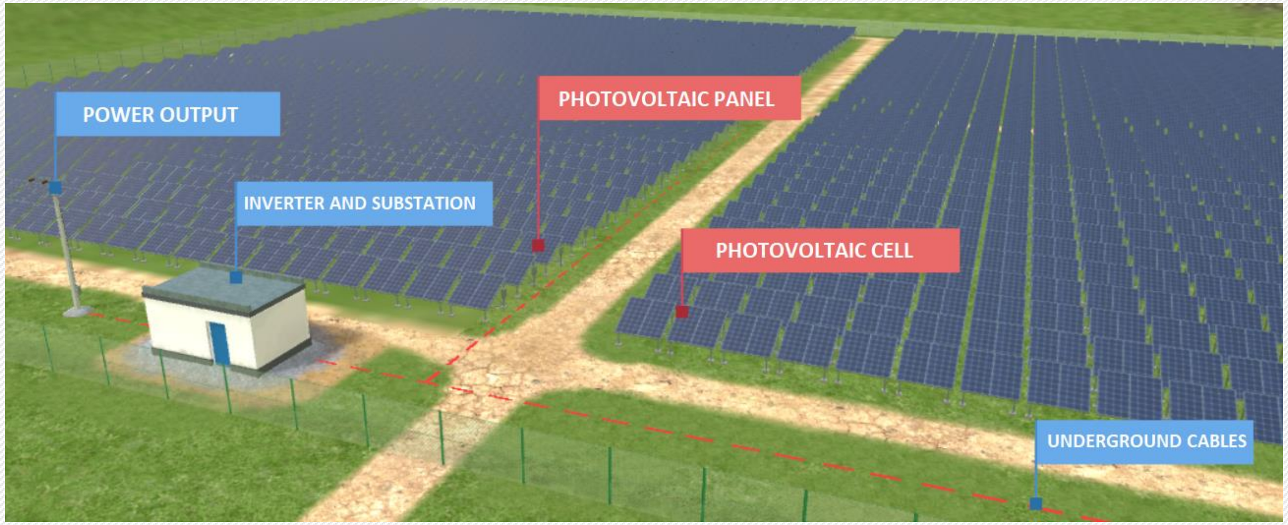
a) Batteries - most often lead or more expensive lithium batteries. Lithium batteries have a longer lifetime and are smaller and lighter. It is important to choose the right battery capacity. This is calculated from various factors such as consumption curves, power plant installation capacity, the amount of investment resources or the amount of potential subsidies.

b) Water heating - a properly designed and implemented photovoltaic system can use up to 100% of the electricity generated by direct consumption and accumulation. When accumulating electric energy by heating water, the power of the PV plant is converted by heating coils into thermal energy that heats the water in the boiler.

Net-metering - is a system of connecting a domestic source of electricity to the distribution grid, which allows its owner to consume electricity at a time other than when it was produced. The owner of the plant is equipped with a bidirectional electricity meter, which in the case of surplus turns to the other side and the energy is supplied to the distribution grid. The household electricity bill then represents the difference between its production and consumption.

High-power photovoltaic power plants

- The vast majority of PV plants take up a large area and use PV panels placed on a stable, simple structure with fixed panel orientation and inclination. Equipping all the panels of a large power plant with a solar tracking system is more demanding on finance and operational maintenance. PV panels generate DC current. Power plants must therefore be equipped with an AC inverter to be connected to the local distribution grid.

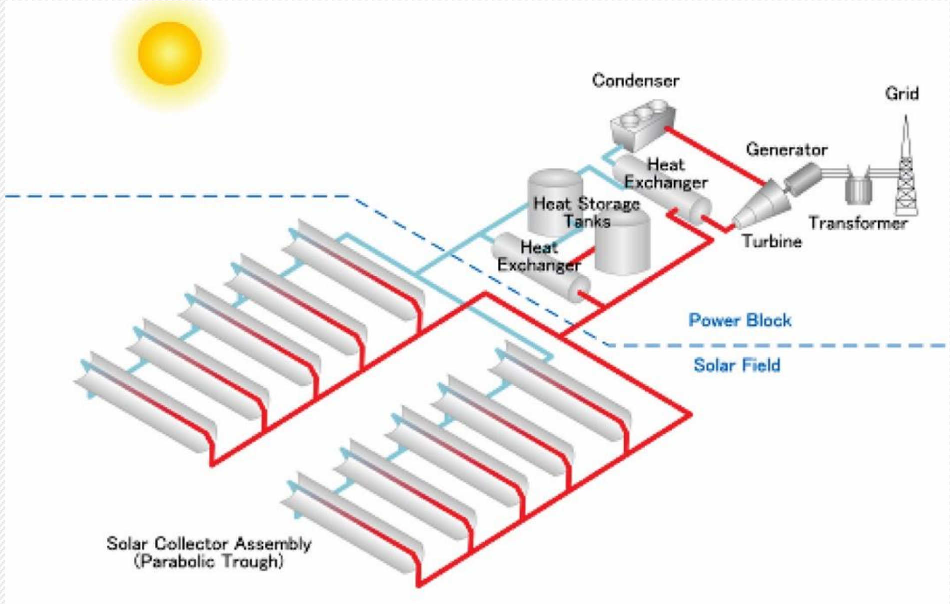


- PV panels are most effective in mountain areas where the temperature is low and the atmosphere is clean. The efficiency of PV panels decreases with increasing ambient temperature and atmospheric pollution, which creates an unusable diffuse radiation.

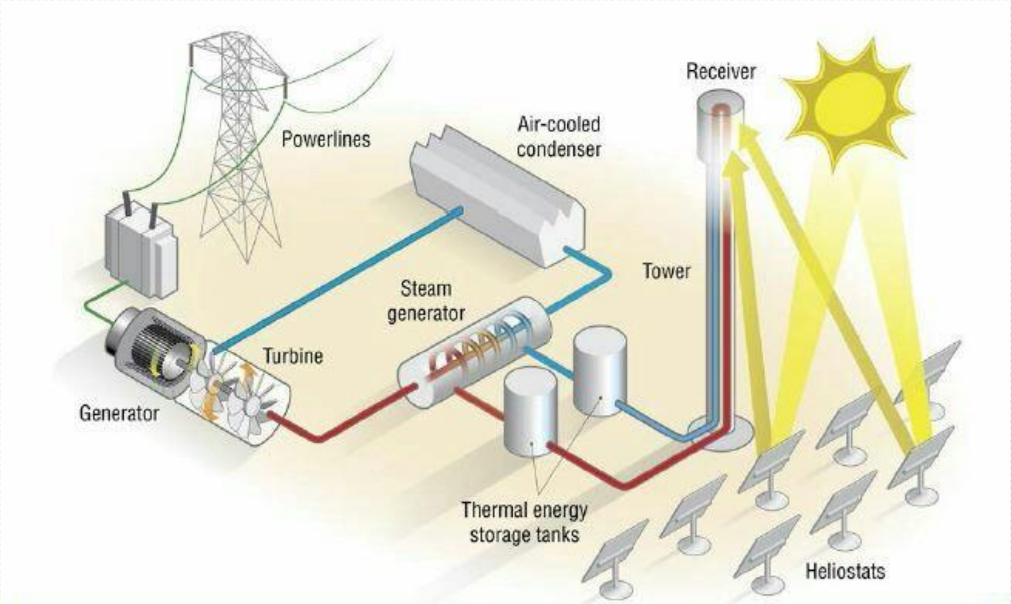
High-power thermal power plants - CSP (concentrated solar power)

Rankine (Clausius-Rankine cycle) or Organic Rankine cycle (ORC), or gas and steam-gas cycles. These two options are currently the most common:

a) Parabolic trough – heat transfer medium is for example thermo-oil, troughs rotate in one axis and track the sun



b) Tower – uses movable heliostats. The heliostats move in two axes



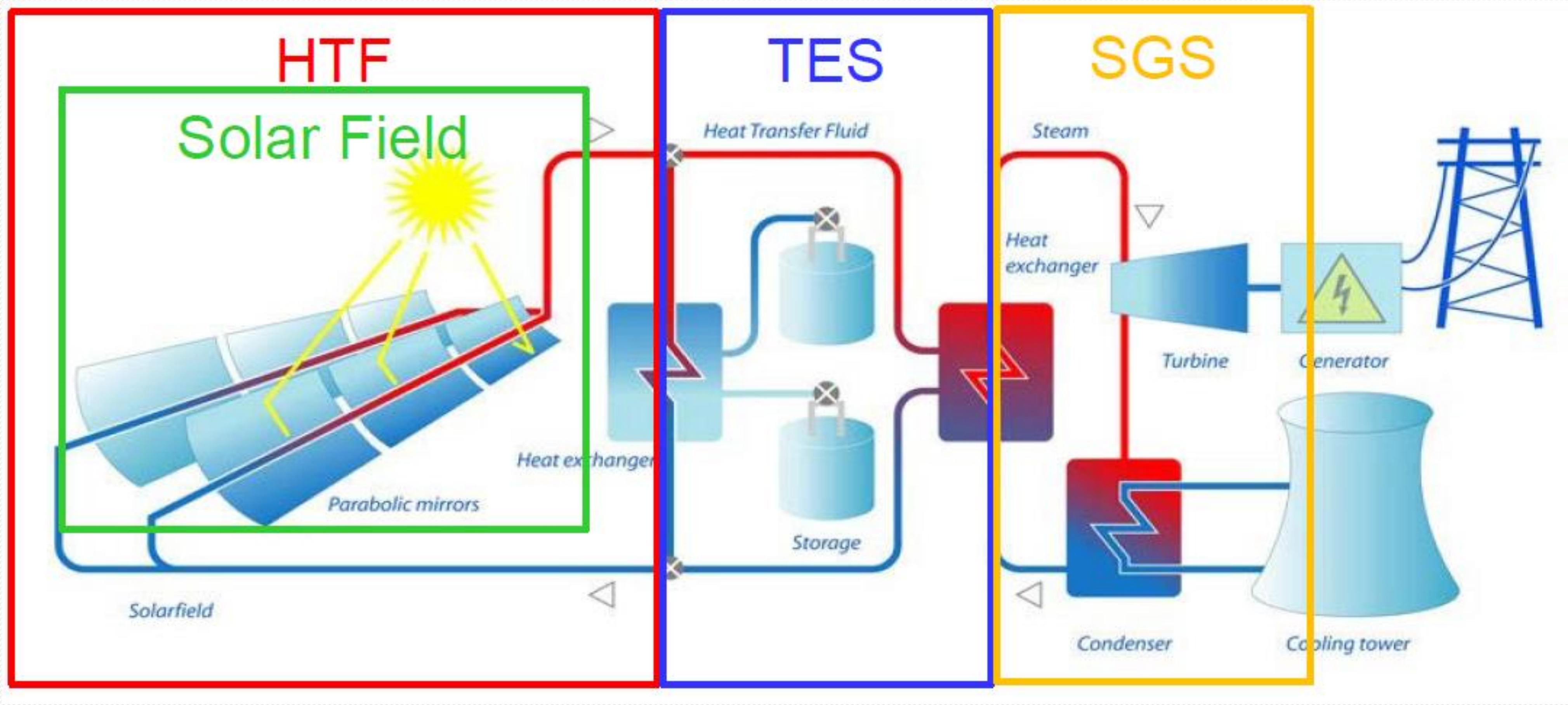
Thermal Power Plant (park type) - parabolic trough

Trough solar collectors belong to the group of concentration collectors (using mirrors). They use the principle of concentrating solar radiation from a larger area into the smallest focal point with a dark tubular absorber, where the radiation heats the heat transfer medium. They reach temperatures around 400°C and are suitable for generating electricity in park solar power plants. The mirror surface is coated with a shiny metal (aluminum or galvanized silver) to increase the reflectance of the mirror. A tube with heat transfer medium, which in most cases is oil, can be designed as a Dewar vessel - a vacuum insulated thermos flask to minimize losses. The thermal efficiency of the gutter collectors achieves up to 90% with a good reflective surface. The heat transfer medium then transfers heat to water (or organic matter - ORC systems), which evaporates and expands in a turbine that spins the generator generating electricity.

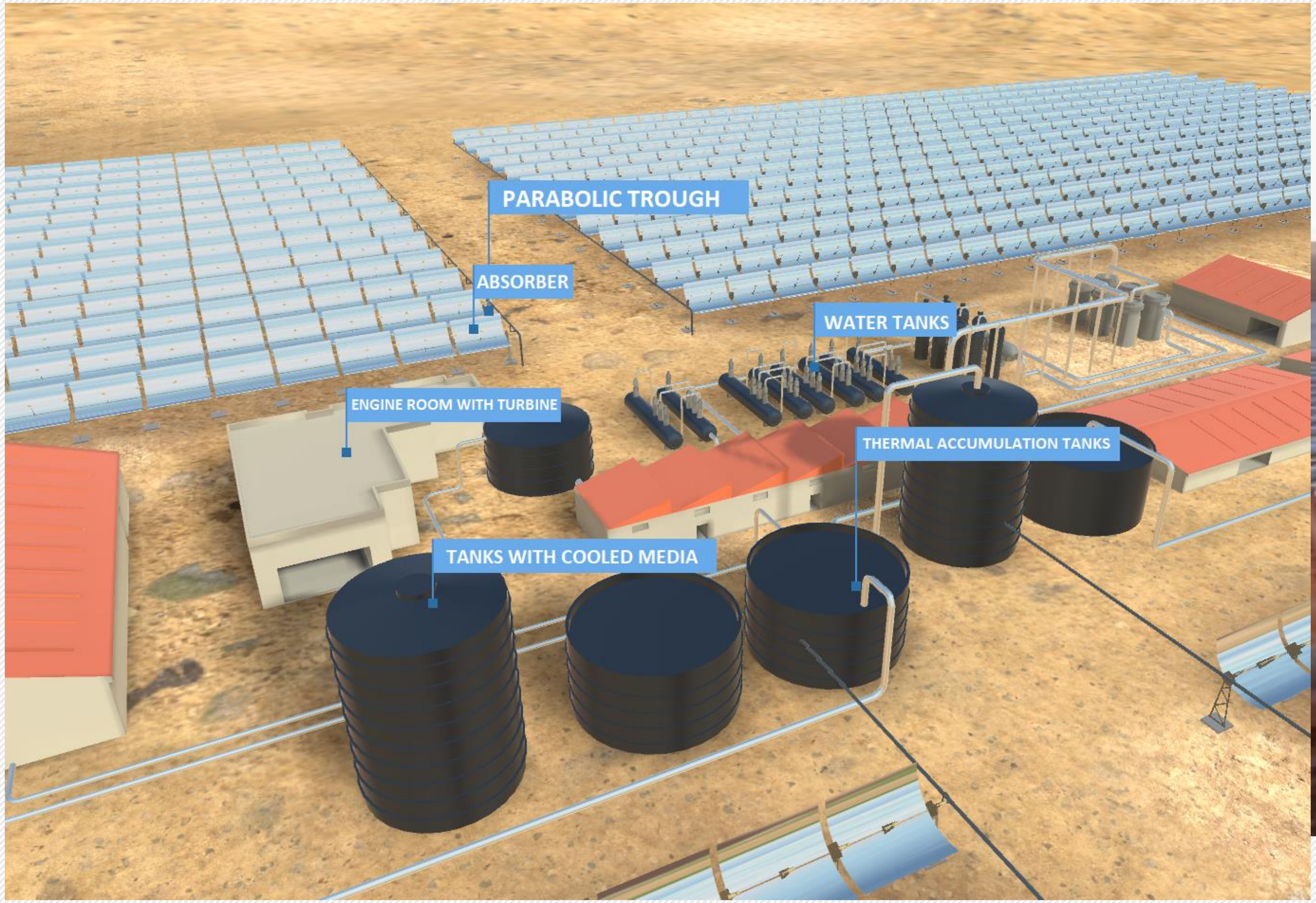
Thermal Power Plant (park type) - parabolic trough

The orientation of the axis of the parabolic troughs is most often in the north-south direction, with the entire collector rotating in the longitudinal axis during the day, following the apparent position of the Sun on the horizon. The system oriented east-west has lower efficiency, but on the other hand it does not need daily turning of the troughs, only small seasonal adjustments of the collector position according to the current height of the Sun. A common component of today's solar thermal power plants is the thermal energy storage system. This makes it possible to produce electricity at night and in the absence of solar radiation. Thermal energy can be stored by sensible heat, latent heat, thermochemical heat or sorption heat (the last two technologies are currently under development). For the first two technologies, molten salt substances (i.e. sodium nitrate or potassium nitrate eutectic) are currently considered as the most promising storage media.

Solar Thermal Power Plant (park type) - parabolic trough



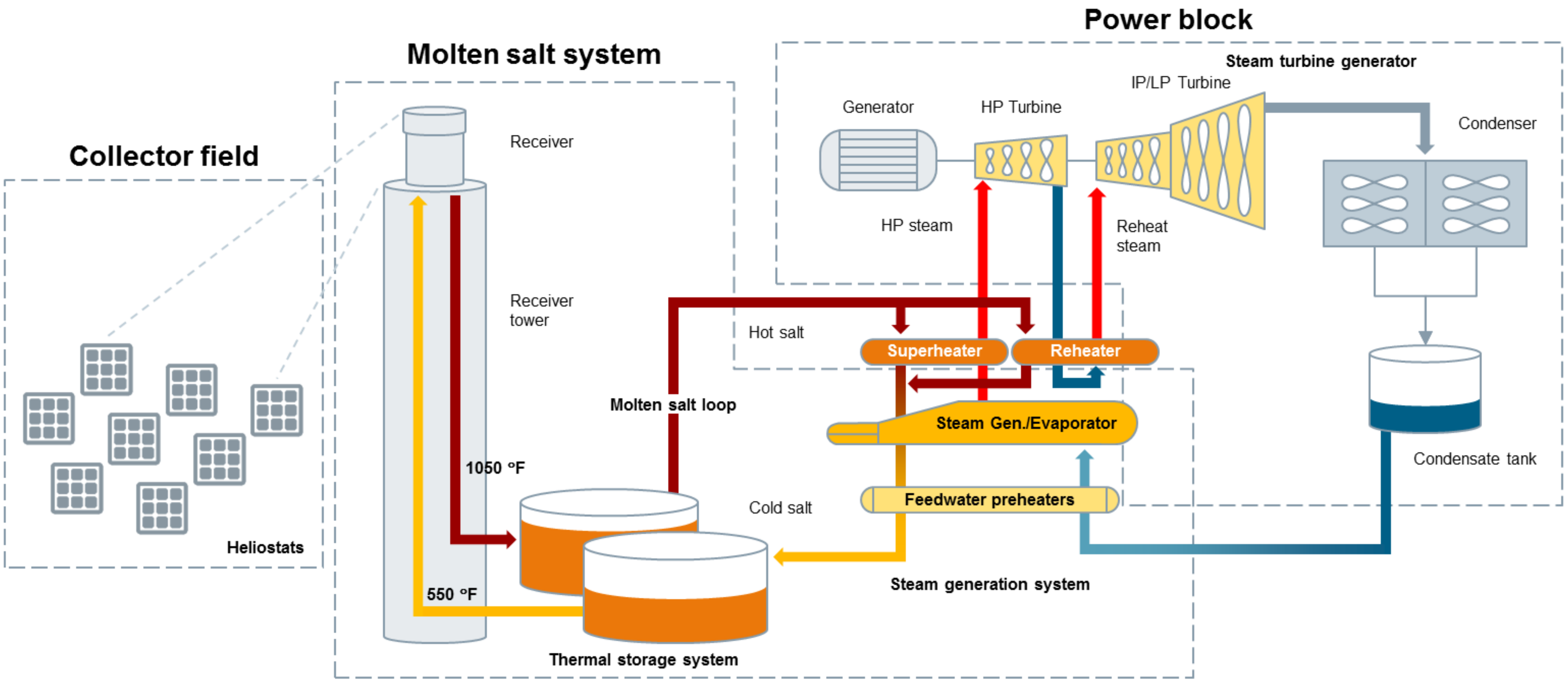
Solar Thermal Power Plant (park type) - parabolic trough



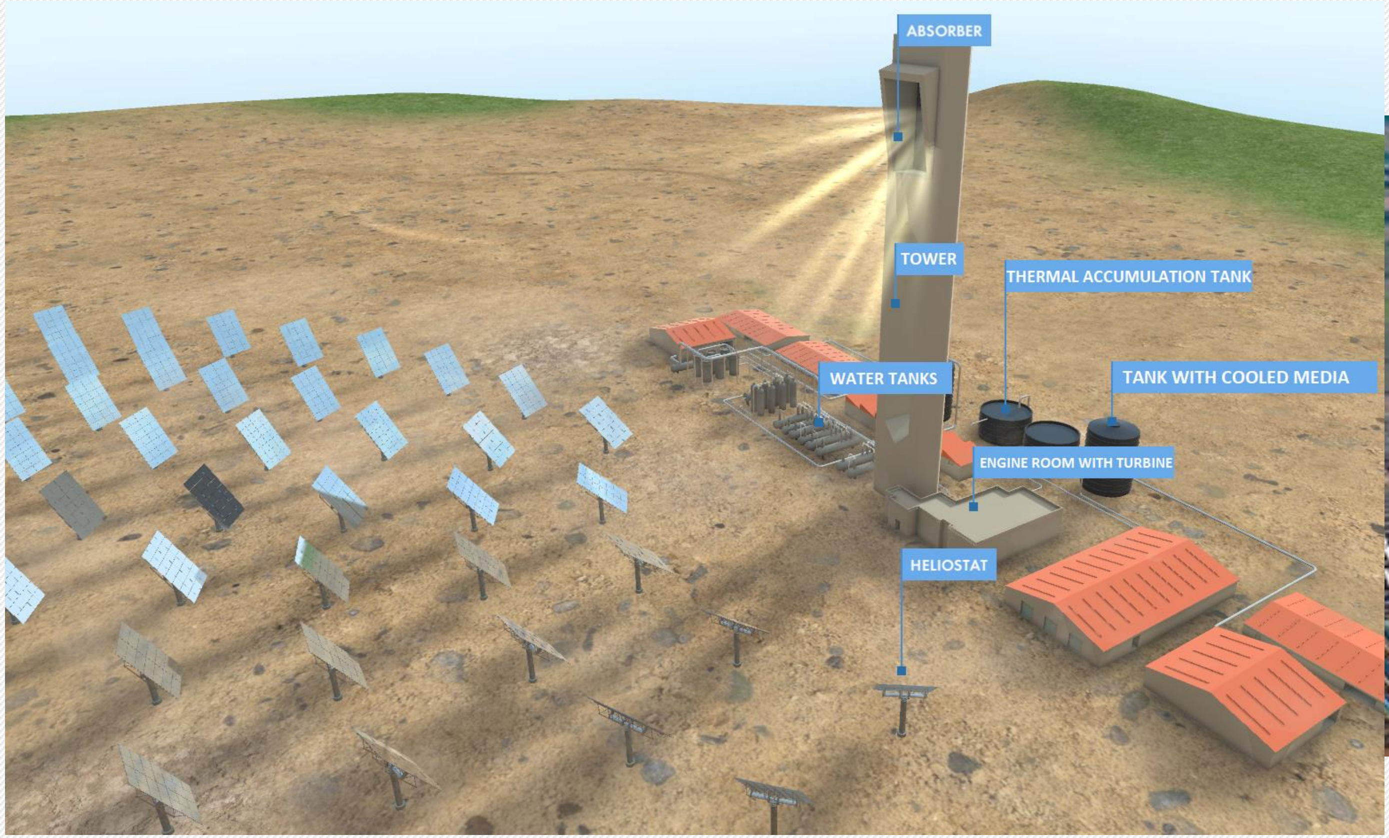
Tower thermal power plant - plane and movable mirrors in two axes (heliostats)

The absorber, where the solar radiation is concentrated, is located at the top of the tower. Solar energy is concentrated into a small absorber space using planar mirrors - heliostats, located around the central tower. Each heliostat has its own biaxial position tracking system. The computer continually calculates the position of the Sun and adjusts the position of the heliostat every few seconds to reflect the sun's radiation at one point at the top of the tower. Inside the absorber, either the heat transfer fluid that drives the turbine with the electric generator is directly overheated, or some of the solar energy is stored in heat accumulators containing molten salts. Due to the high concentration of incident energy, relatively high temperatures of up to 1000 ° C and potentially more are achieved in the absorber. This also improves the efficiency of heat utilization when converting to electricity.

Tower thermal power plant - plane and movable mirrors in two axes (heliostats)



Tower thermal power plant - plane and movable mirrors in two axes (heliostats)



Links to investigate

- https://www.youtube.com/watch?v=w1tPNmTwSKI&t=58s
- https://www.youtube.com/watch?v=LMWIgwvbrcM&t=190s
- https://www.youtube.com/results?search_query=CSP+solar
- or google it…

Thank you for your attention